Final Report

on

NAG1-1789

RADIATION TRANSPORT AND SHIELDING FOR SPACE EXPLORATION AND HIGH SPEED FLIGHT TRANSPORTATION

Principal Investigator:

Dr. Khin Maung Maung
Department of Physics
Hampton University
Hampton, Virginia 23668

Phone:(757) 727-5826
emil: MAUNG@CEBAF.GOV

Final Report on NASA Grant NAG1-1789

Title: Radiation Transport and High Speed Flight Transportation for Space Exploration and High Speed Flight Transportation

Principal Investigator:	**Dr. Khin Maung Maung**
Senior Scientist:	**Dr. R. K. Trapathi**
Institution:	**Department of Physics** **Hampton University**

Transportation of ions and neutrons in matter is of direct interest in several technologically important and scientific areas, including space radiation, cosmic ray propagation studies in galactic medium, nuclear power plants and radiological effects that impact industrial and public health. For the proper assessment of radiation exposure, both reliable transport codes and accurate data are needed. Nuclear cross section data is one of the essential inputs into the transport codes. In order to obtain an accurate parametrization of cross section data, theoretical input is indispensable especially for processes where there is little or no experimental data available.

In this grant period work has been done on the studies of the use of relativistic equations and their one-body limits. The results will be useful in choosing appropriate effective one-body equation for reaction calculations. Work has also been done to improve upon the data base needed for the transport codes used in the studies of radiation transport and shielding for space exploration and high speed flight transportation. A phenomenological model was developed for the total absorption cross sections valid for any system of charged and/or uncharged collision pairs for the entire energy range. The success of the model is gratifying. It is being used by other federal agencies, national labs and universities. A list of publications based on the work during the grant period is given below and copies are enclosed with this report.

(1). One-Body Limits of Two-Body Relativistic Equations, in "Quark Confinement and the Hadron Spectrum II", page 380, World Scientific, Edt. N. Brambilla and G. M. Prosperi. 1996

(2) Universal parametrization of absorption cross sections, NASA TP 3621

(3) Accurate universal parametrization of absorption cross section, Nucl. Instr. Meth. Phys. Res. B 117 (1996)347.

(4) Accurate universal parametrization of absorption cross section II, Nucl. Instr. Meth. Phys. Res. B 129 (1997) 11.

Quark Confinement and the Hadron Spectrum II

Como, Italy 26 – 29 June 1996

Editors

N. Brambilla & G. M. Prosperi

Università degli Studi di Milano and Istituto Nazionale di Fisica Nucleare, Italy

World Scientific

Singapore • New Jersey • London • Hong Kong

ONE-BODY LIMITS OF TWO-BODY RELATIVISTIC EQUATIONS

Trina L. Christian and Khin Maung Maung
Department of Physics, Hampton University, Hampton VA 23668

John W. Norbury
Department of Physics, University of Wisconsin, Milwaukee, WI 54601

The bound state spectra of the Blankenbecler- Sugar, Kadyshevsky and Gross equations with a linearly confining interaction are studied. As a result of the lack of retardation in the interaction, all of these equations approach the same one-body limit, but the rates of approach are different. Numerical results show that the one-body limit is reached when $m_2/m_1 = 10$ for this particular interaction.

In a two particle system of masses m_1 and m_2, in the limit that m_1 or m_2 goes to infinity the relativistic equation for this system should be one which describes the motion of the lighter particle in the instantaneous field of the heavier particle; the relative energy between the particles is zero. This is known as the one-body limit. The Blankenbecler-Sugar[1], Kadyshevsky[2], and Gross[3] equations are studied to determine how the one-body limit is approached as m_2 is increased with m_1 fixed. The momentum space two-body relativistic bound state equations are solved with a confining potential without retardation.[4]

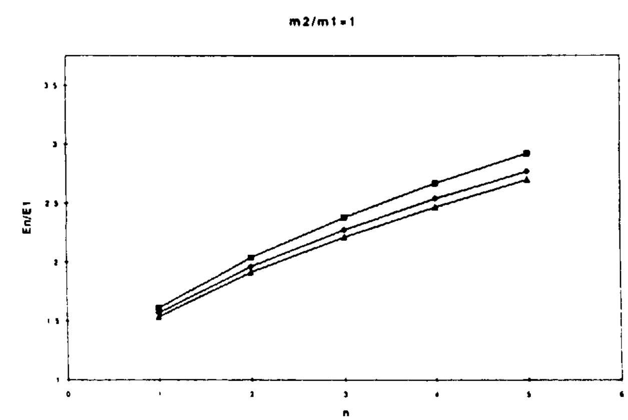
A wide class of relativistic two-body propagators can be written as

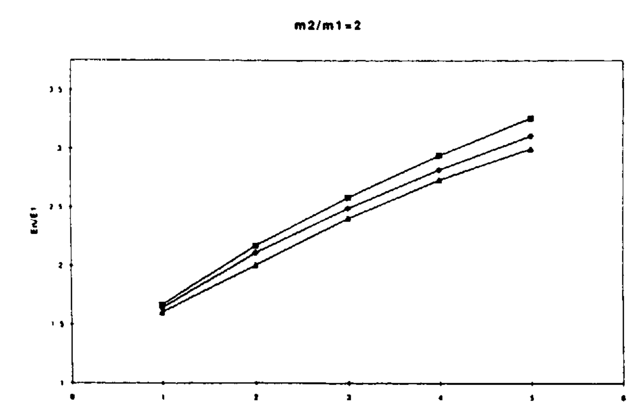
$$g(s', s) = -2\pi i \int \frac{f(s', s)}{s' - s + i\eta} \delta^{(+)}(A)\delta^{(+)}(B)\, ds'$$

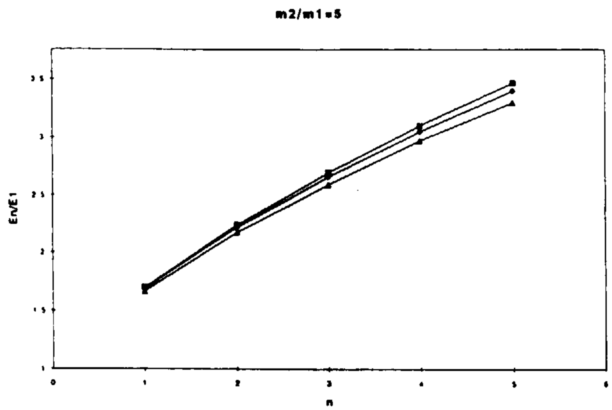
where k and P are the relative and total four-momenta and $f(s', s)$ is any function that satisfies the constraint $f(s, s) = 1$. Therefore in principle there exist an infinite number of three-dimensional equations.[5] The choices for A and B in the arguments of the delta functions are chosen to distinguish between one particle on-mass-shell systems and both particles equally off-mass-shell. For one particle on-mass-shell systems, Type I, $A = (aP + k)^2 - m_1^2$ and $B = (P' - aP - k)^2 - m_2^2$ and $A = (aP' + k) - m_1^2$ and $B = (bP' - k)^2 - m_2^2$ for Type II, both particles equally off-mass-shell. In order to have a one-body limit in three-dimensional equations, we use the Wightman-Garding variables[6,7], a and b; $a = (s + m_1^2 - m_2^2)/2s$ and $b = (s + m_2^2 - m_1^2)/2s$ where s is the total

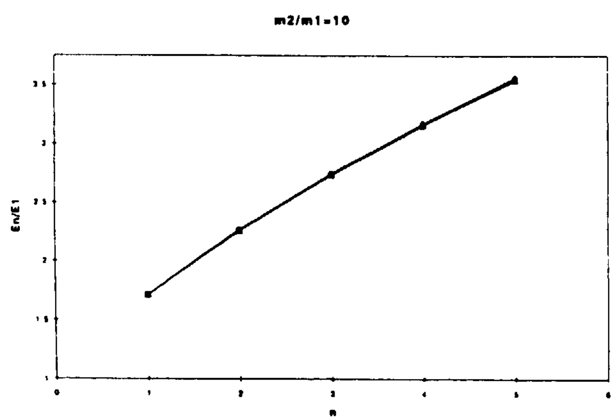
four-momentum squared. Explicit forms of propagators in the center-of-mass frame have been tabulated.[8] The Blankenbecler-Sugar propagator is Type II, while the Kadyshevsky and Gross propagators are Type I.

In these preliminary calculations, we study the bound state spectrum of these equations with a linear confining interaction without retardation. The figures represent each of the three equations evaluated with increasing m_2. In figures (1) to (4) the mass ratios are 1,2,5 and 10 respectively. In each figure, squares, diamonds and triangles represent the Kadyshevsky, Blankenbecler-Sugar and Gross results.









The curves display important revelations: for this particular interaction, the various equations approach the same one-body limit at different rates, and a mass ratio is determined for a two particle bound state system to reach the one-body limit at m_2 to m_1 equal 10.

The results can be understood in the following way. As m_1 or m_2 goes to infinity the choice of type becomes insignificant. The function $f(s', s)$ goes to unity as well if one particle mass goes to infinity. Therefore for any nonretarded interaction, they all have the same one-body limit. Although a one-body limit

was reached, the Klein-Gordon result was not obtained. This shortcoming is attributed to additional multiplicative terms that vary from one propagator to the next but nevertheless prevent the Klein-Gordon limit from being reached.[9] However, $f(s', s)$ does not equal one in general. This accounts for the difference in the rates of approach to the one-body limit for the different equations.

In conclusion, it is shown that the same one-body limit is reached for Type I and Type II equations without retardation in the interaction. This can be helpful when evaluating a two particle system; the results suggest that a one-body equation should not be used if the mass ratios of the particles are not consistent with the results obtained above, at least for this particular interaction. This type of study should also be considered for scattering problems where the use of a one-body equation is very common.

Acknowledgements

T.L.C and K.M.M. would like to thank the National Science Foundation grant HRD 9633750, NASA grant NAG 1 1789 and the Virginia Space Grant Consortium.

1. R. Blankenbecler, R. Sugar, *Phys. Rev.*, **142**, (1966), 1051.
2. V. Kadyshevsky, *Nucl. Phys. B*, **6**, (1968), 125.
3. F. Gross, *Phys. Rev.*, **186**, (1969), 1448.
4. K. M. Maung, D. E. Kahana and J. W. Norbury, *Phys. Rev. D*, **47**, (1993), 1182.
5. R. J. Yaes, *Phys. Rev. D*, **3**, (1971), 3086.
6. A. J. MacFarlane, *Rev. Mod. Phys.*, **34**,(1962), 42.
7. P. C. Tiemeijer, J. A. Tjon, *Phys. Rev. C*, **49**, (1994), 494.
8. J. Frolich, K. Schwarz, H. F. K. Zingl, *Phys. Rev. C*, **27**, (1983), 265.
9. E. D. Cooper, B. K. Jennings, *Nucl. Phys. A*, **500**,(1989), 553.

Reprinted from

NIM B

Beam Interactions with Materials & Atoms

Nuclear Instruments and Methods in Physics Research B 117 (1996) 347-349

Accurate universal parameterization of absorption cross sections

R.K. Tripathi [a,b,*], Francis A. Cucinotta [c], John W. Wilson [c]

[a] *Southern Illinois University, Carbondale, IL 62901, USA*
[b] *Hampton University, Hampton, VA 23668, USA*
[c] *NASA Langley Research Center, Hampton, VA 23681, USA*

Received 8 April 1996; revised form received 8 May 1996

N·H
ELSEVIER

BEAM INTERACTIONS WITH MATERIALS AND ATOMS
Nuclear Instruments and Methods in Physics Research – Section B

Aims and scope

Section B of Nuclear Instruments and Methods in Physics Research (NIM B) provides a special forum for the discussion of all aspects of the interaction of energetic beams with atoms, molecules and aggregate forms of matter. This includes ion beam analysis and ion beam modification of materials, as well as studies of the basic interaction mechanisms of importance for this work. The Editors invite submission of both theoretical and experimental papers of original research in this area.

Subscription information 1997

Volumes 121–133 of Nuclear Instruments and Methods in Physics Research - Section B (ISSN 0168-583X) are scheduled for publication. A combined subscription to NIM A volumes 384–401 and NIM B volumes 121–133 is available at a reduced rate. Subscriptions are accepted on a prepaid basis only and are entered on a calendar year basis. Issues are sent by SAL (Surface Air Lifted) mail wherever this service is available. Airmail rates are available upon request. Please address all enquiries regarding orders and subscriptions to:

Elsevier Science B.V.
Order Fulfillment Department
P.O. Box 211, 1000 AE Amsterdam
The Netherlands
Tel. +31 20 485 3642, fax: +31 20 485 3598

Claims for issues not received should be made within six months of our publication (mailing) date.

Abstracted/indexed in:

Current Contents: Engineering, Technology and Applied Sciences; EI Compendex Plus; Engineering Index; INSPEC; Physics Briefs.

US Mailing notice: Nuclear Instruments and Methods in Physics Research - Section B (ISSN 0168-583X) is published semi-monthly (for nine months of the year), and monthly in January, October and November, by Elsevier Science B.V., Molenwerf 1, P.O. Box 211, 1000 AE Amsterdam, The Netherlands. Annual subscription price in the USA is US$ 5930 (valid in North, Central and South America only), including air speed delivery. Periodicals postage paid at Jamaica, NY 11431.

USA Postmasters: Send address changes to Nuclear Instruments and Methods in Physics Research - Section B, Publications Expediting, Inc., 200 Meacham Avenue, Elmont, NY 11003. Airfreight and mailing in the USA by Publications Expediting Inc.

∞ The paper used in this publication meets the requirements of ANSI/NISO Z39.48-1992 (Permanence of Paper).

Printed in The Netherlands

North-Holland, an imprint of Elsevier Science

ELSEVIER

ELSEVIER

Nuclear Instruments and Methods in Physics Research B 117 (1996) 347-349

NIM B
Beam Interactions
with Materials & Atoms

Accurate universal parameterization of absorption cross sections

R.K. Tripathi [a,b,*], Francis A. Cucinotta [c], John W. Wilson [c]

[a] Southern Illinois University, Carbondale, IL 62901, USA
[b] Hampton University, Hampton, VA 23668, USA
[c] NASA Langley Research Center, Hampton, VA 23681, USA

Received 8 April 1996; revised form received 8 May 1996

Abstract

We present a simple universal parameterization of total reaction cross sections for any system of colliding nuclei valid for the entire energy range from a few A MeV to a few A GeV. The universal picture presented here treats the proton–nucleus collision as a special case of the nucleus-nucleus collision, where the projectile has charge and mass number one. The parameters are associated with the physics of the collision system. In general terms Coulomb interaction modifies cross sections at lower energies and the effects of Pauli blocking are important at higher energies. The agreement between the calculated and experimental data is better than all earlier published results.

1. Introduction

The transportation of energetic ions in bulk matter is of direct interest in several areas [1] including shielding against ions originating from either space radiations or terrestrial accelerators, cosmic ray propagation studies in galactic medium or radiobiological effects resulting from the work place or clinical exposures. For carcinogenesis, terrestrial radiation therapy, and radiobiological research, knowledge of the beam composition and interactions is necessary to properly evaluate the effects on human and animal tissues. For the proper assessment of radiation exposures both reliable transport codes and accurate input parameters are needed.

One such important input is the total reaction cross section, defined as the total minus the elastic cross sections for two colliding ions:

$$\sigma_R = \sigma_T - \sigma_{el}. \tag{1}$$

In view of its importance the total reaction cross section has been extensively studied both theoretically [1-14] and experimentally [15-20] for the past five decades. A detailed list of references is given in Refs. [1,13,16]. Empirical prescriptions have been developed [2-4,10,11,13] for the total reaction cross sections working in various energy ranges and combination of interacting ions. The present model works in all energy ranges for any combination of interacting ions including proton–nucleus collisions and is more accurate than earlier reported empirical models.

* Corresponding author. Tel. +1 804 864 1467, fax +1 804 864 8094, e-mail rkt@hesb1.larc.nasa.gov

2. Model description

The present model is an updated and revised version of the empirical model developed at NASA Langley Research Center and reported earlier [10]. Most of the empirical models approximate the total reaction cross section of the Bradt–Peters form:

$$\sigma_{abs} = \pi r_0{}^2 (A_P^{1/3} + A_T^{1/3} - \delta)^2, \tag{2}$$

where r_0 is energy independent and δ is either an energy-independent or energy dependent parameter, and A_P and A_T are the projectile and target mass numbers, respectively. This form of parameterization works nicely for higher energies. However, for lower energies Coulomb interaction becomes important and modifies the reaction cross sections significantly. In addition, strong absorption models suggest an energy dependence of the interaction radius. Incorporating these effects, and other effects discussed later in the text, we propose the following form for the reaction cross section:

$$\sigma_R = \pi r_0^2 (A_P^{1/3} + A_T^{1/3} + \delta_E)^2 (1 - B/E_{cm}). \tag{3}$$

We notice that the Coulomb interaction, where r_0 = 1.1 fm, and E_{cm} is in MeV, modifies the cross sections at lower energies and gets less important as the energy increases (typically after several tens of A MeV). In Eq. (3) B is the energy dependent Coulomb interaction barrier (right hand factor in Eq. (3)), and is given by

$$B = 1.44 Z_P Z_T / R, \tag{4}$$

where

$$R = r_P + r_T + 1.2(A_P^{1/3} + A_T^{1/3})/E_{cm}^{1/3}, \tag{5}$$

PII S0168-583X(96)00331-X

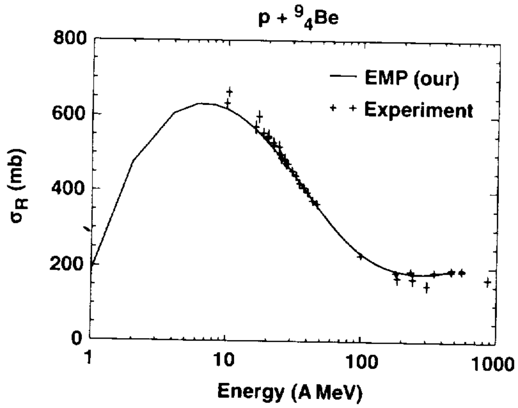


Fig. 1. Absorption cross sections for the proton-beryllium collision as a function of proton kinetic energy. The solid line represents present model and the experimental data are from Ref. [15].

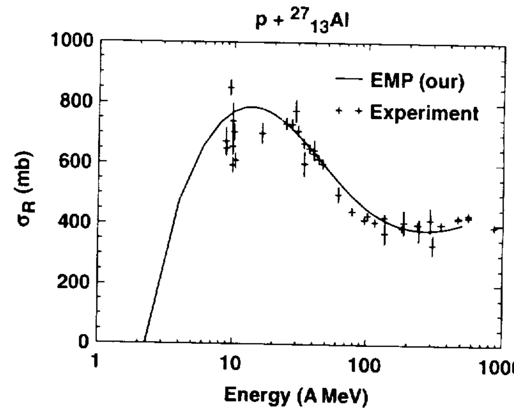


Fig. 2. Absorption cross sections for the proton-aluminum collision as a function of proton kinetic energy. The solid line represents the present model and the experimental data are from Ref. [15].

with (i = P, T)

$$r_i = 1.29(r_i)_{\rm rms}. \tag{6}$$

There is an energy dependence in the reaction cross section at intermediate and higher energies mainly due to two effects – transparency and Pauli blocking. This is taken into account in δ_E, which is given by

$$\delta_E = 1.85S + 0.16\frac{S}{E_{\rm cm}^{1/3}} - C_E + 0.91\frac{(A_{\rm T} - 2Z_{\rm T})Z_{\rm P}}{A_{\rm T}A_{\rm P}}, \tag{7}$$

where S is the mass asymmetry term and is given by

$$S = A_{\rm P}^{1/3}A_{\rm T}^{1/3}/(A_{\rm P}^{1/3} + A_{\rm T}^{1/3}) \tag{8}$$

and is related to the volume overlap of the collision system. The last term on the right hand side of Eq. (7) accounts for the isotope dependence of the reaction cross section. The term C_E is related to the transparency and Pauli blocking and is given by

$$C_E = D(1 - \exp(-E/40)) - 0.292\exp(-E/792) \times \cos(0.229E^{0.453}). \tag{9}$$

Here D is related to the density dependence of the colliding system scaled with respect to the density of the C+C system, i.e.:

$$D = 1.75(\rho_{A_{\rm P}} + \rho_{A_{\rm T}})/(\rho_{A_{\rm C}} + \rho_{A_{\rm C}}). \tag{10}$$

The density of a nucleus is calculated in the hard sphere model [24], and for a nucleus of mass number A_i is given by

$$\rho_{A_i} = A_i/\tfrac{4}{3}\pi r_i^3, \tag{11}$$

where the radius of the nucleus r_i is defined in Eq. (6) with the root-mean-square radius, $(r_i)_{\rm rms}$, obtained directly from experiment [25]. There is interesting physics associated with the constant D. This in effect simulates the modifications of the reaction cross sections due to Pauli blocking. This effect is new and has not been taken into account in other empirical calculations. This helps present a universal picture of the reaction cross sections.

At lower energies (below several tens of A MeV) where the overlap of interacting nuclei is small (and where Coulomb interaction modifies the reaction cross sections significantly) the modifications of the cross sections due to Pauli blocking are small, and gradually play an increasing role as the energy increases, since this leads to higher densities where Pauli blocking gets increasingly important. Interestingly enough for the proton–nucleus case, since there is not much compression effect, a single constant value of D = 2.05 gives very good results for all proton–nucleus collisions. For alpha–nucleus collisions, where there is a little compression, the best value of D is given by

$$D = 2.77 - 8.0\times10^{-3}A_{\rm T} + 1.8\times10^{-5}A_{\rm T}^2 - 0.8/(1 + \exp(250 - E)/75). \tag{12}$$

For lithium nuclei because of the "halos", compression is less and hence the Pauli blocking effect is less important and a reduced value of $D/3$ gives better results for the reaction cross sections at the intermediate and higher energies.

There are no adjustable parameters in the model except that for proton–nucleus collisions this method of calculating the Coulomb energy underestimates its value for the very light closed shell nuclei of alpha and carbon, and these should be increased by a factor of 27 and 3.5 respectively for a better fit.

3. Results/conclusions

Typical results obtained from the model are shown in Figs. 1 through 5. Agreement with experimental data is excellent and is better than all other empirical models reported earlier. This is particularly important in view of the fact that the agreement is excellent throughout the whole energy

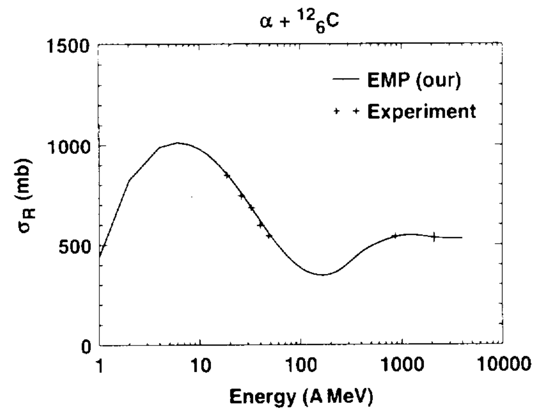


Fig. 3. Absorption cross sections for the alpha–carbon collision as a function of incident ion kinetic energy. The solid line represents present model and the experimental data are from Refs. [21,22].

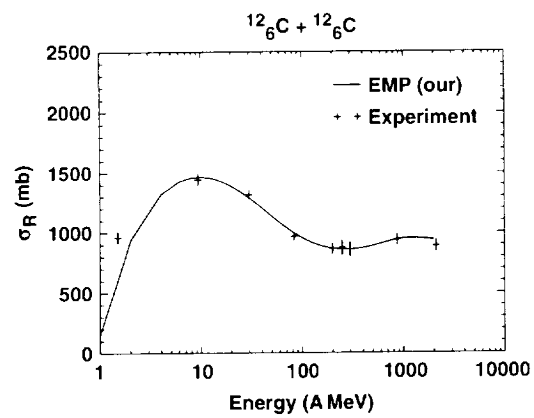


Fig. 4. Absorption cross sections for the carbon–carbon collision as a function of incident ion kinetic energy. The solid line represents the present model and the experimental data are from Refs. [1,9,13,16].

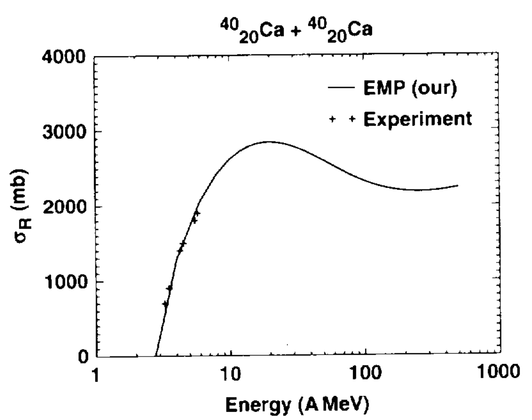


Fig. 5. Absorption cross sections for the calcium–calcium collision as a function of incident ion kinetic energy. The solid line represents the present model and the experimental data are from Refs. [1,9,13,16].

range – up to a few A GeV. The model has been tested with all the available data for projectiles proton through krypton and targets alpha through bismuth for the energy range from a few A MeV up to a few A GeV and is found to give excellent results for all the systems throughout the energy range. In view of the simplicity and accuracy of the model it is a welcome improvement for transport calculations.

It will be interesting to see how the model compares with the new experimental data as and when these become available.

Acknowledgements

One of the authors (R.K.T.) acknowledges NASA Langley Research Center for the support.

References

[1] J.W. Wilson et al., NASA RP-1257, December 1991.
[2] R. Bass, Nuclear Reactions with Heavy Ions (Springer, Berlin, 1980).
[3] H.L. Bradt and B. Peters, Phys. Rev. 77 (1950) 54.
[4] P.J. Karol, Phys. Rev. C 11 (1975) 1203.
[5] R.J. Glauber, in: Lectures in Theoretical Physics, Vol. 1, ed. Brittin (Interscience, New York, 1959) p. 315.
[6] J.W. Wilson, Composite particle reaction theory, Ph.D. dissertation, College of William and Mary in Virginia, June 1975.
[7] J.W. Wilson and L.W. Townsend, Can. J. Phys. 59 (1981) 1569.
[8] D.J. Ernst, Phys. Rev. C 19 (1979) 896.
[9] S.K. Gupta and S. Kailash, Z. Phys. 317 (1984) 75; S.K. Gupta and P. Shukla, Phys. Rev. C 52 (1995) 3212.
[10] L.W. Townsend and J.W. Wilson, Rad. Res. 106 (1986) 283.
[11] W. Shen, B. Wang, J. Feng, W. Zhan, Y. Zhu and E. Feng, Nucl. Phys. A 491 (1989) 130.
[12] A. Vituri and F. Zardi, Phys. Rev. C 36 (1987) 1404.
[13] L. Sihver, C.H. Tsao, R. Silberberg, T. Kanai and A.F. Barghourty, Phys. Rev. C 47 (1993) 1225.
[14] R.M. DeVries and J.C. Peng, Phys. Rev. 22 (1980) 527.
[15] W. Bauhoff, Atom. Data Nucl. Data Tables 35 (1986) 429.
[16] S. Kox, A. Gamp, C. Perrin, J. Arvieux, R. Bertholet, J.F. Bruandet, M. Buenerd, R. Cherkaoui, A.J. Cole, Y. El-Masri, N. Longequeue, J. Menet, F. Merchez and J.B. Viano, Phys. Rev. C 35 (1987) 1678, and references therein.
[17] V.S. Barashenkov, K.K. Gudima and V.D. Toneev, Prog. Phys. 17 (1969) 693.
[18] W.R. Webber, J.C. Kish and D.A. Schrier, Phys. Rev. C 41 (1990) 547.
[19] L.V. Dubar, D.Sh. Eeukenov, L.I. Slyusarenko and N.P. Yurkuts, Sov. J. Nucl. Phys. 49 (1989) 771.
[20] J.J. Menet, E.E. Gross, J.J. Malanify and A. Zucker, Phys. Rev. C 4 (1971) 1114.
[21] J. Jaros, A. Wagner, L. Anderson, O. Chamberlain, R.Z. Fuzesy, J. Gallop, W. Gorn, L. Schroeder, S. Shannon, G. Shapiro and H. Steiner, Phys. Rev. C 18 1978) 2273.
[22] A. Auce, R.F. Carlson, A.J. Cox, A. Ingemarsson, R. Johansson, P.U. Renberg, O. Sundber, G. Tibell and R. Zorno, Phys. Rev. C 50 (1994) 871.
[23] R.K. Tripathi, F.A. Cucinotta and J.W. Wilson, NASA TP, under preparation.
[24] R.K. Tripathi, L.W. Townsend and F.W. Khan, Phys. Rev. C 47 (1993) R935.
[25] H. de Vries, C.W. de Jager and C. de Vries, Atom. Data Nucl. Data Tables 36 (1987) 495.

Instructions to Authors

Submission of papers

Contributions should be submitted to one of the Editors (see inside front cover). It is suggested that manuscripts originating from Europe, India, The Middle East and Africa be sent to Prof. H.H. Andersen, and from The Americas, The Far East and Australasia, to Dr. L.E. Rehn.

Manuscript and figures should be submitted in duplicate, with one set of good quality figure material for production of the printed figures. If possible, please submit also an electronic version of your contribution on diskette.

Short contributions of less than 1500 words and not subdivided into sections may be published as Letters to the Editor in a shorter time than regular articles as the proofs will normally be corrected by the Publisher.

Submission of a manuscript implies that it is not being considered for publication elsewhere and that the authors have obtained the necessary authority for publication.

Manuscript preparation

Manuscripts should be written in good English. They should be typed throughout with double line spacing and wide margins on numbered, single column pages. See notes opposite on electronic manuscripts.

Structure. Please adhere to the following order of presentation: article title, author(s), affiliations, abstract, PACS codes and keywords, main text, acknowledgements, appendices, references, figure captions, tables.

Corresponding author. The name, full postal address, telephone and fax numbers and e-mail address of the corresponding author should be given on the first page.

Classification codes/keywords. Please supply one to four classification codes (PACS and/or MSC), and up to six keywords of your own choice that describe the content of your article in more detail.

References to other publications should be numbered consecutively within square brackets and listed together at the end of the text. In the case of multiple authorship all authors should be listed in the references; only in case of more than ten authors is the first author et al. acceptable.

Illustrations

The Publisher requires a set of good quality drawings and original photographs to produce the printed figures.

Line drawings should be 1.5–3 times larger than the printed size; the height of letters and numbers should, after reduction, fall within the range 1.2–2.4 mm. Do not use too narrow pen widths for machine-plotted graphs. Shaded areas should be shown by means of cross-hatching or a matrix of dots, rather than a continuous grey wash.

Photographs should not already be screened (overprinted with the point matrix used by printers). The top side of a photograph should be marked if necessary.

Colour figures can be printed in colour when this is essential to the presentation. Authors will be charged for colour reproduction. Further information can be obtained from the Publisher.

After acceptance

Notification. You will be notified by the Editor of the acceptance of your contribution, and invited to send an electronic file of the accepted version to the Publisher, if this is not yet available. After acceptance any correspondence should be addressed to the Publisher at the coordinates below.

Page proofs are sent out to the Author in order to check that no undetected errors have arisen in the typesetting or file conversion process. In the proofs only typesetting errors may be corrected. No changes in, or additions to, the accepted paper will be accepted.

Copyright transfer. In the course of the production process the authors will be asked to transfer the copyright of the article to the publisher. This transfer will ensure the widest possible dissemination of information.

Electronic manuscripts

If possible, an electronic version of the manuscript should be submitted on a diskette together with the hard copies of the text and figures, or should be sent (after acceptance) by e-mail or on a diskette to the Publisher. It is the responsibility of the Author to ensure that the electronic version exactly matches the hard copy. No deviations from the version accepted for publication are permissible without the prior and explicit approval by the Editor. Such changes should be clearly indicated on an accompanying print-out of the file.

LaTeX articles and articles prepared with any of the well known word processors can be handled by the Publisher. Further information can be obtained from the Publisher.

Author benefits

No page charges. Publishing in Nuclear Instruments and Methods in Physics Research - Section B is free.

Free offprints. The corresponding author1 will receive 50 offprints free of charge. An offprint order form will be supplied by the publisher for ordering any additional paid offprints.

Discount. Contributors to Elsevier Science journals are entitled to a 30% discount on all Elsevier Science books.

Correspondence with the Publisher

After acceptance of an article any correspondence should be addressed to Elsevier Science B.V., NIM-B Editors, P.O. Box 2759, 1000 CT Amsterdam, The Netherlands
Tel. +31 20 485 2500, fax +31 20 485 2431
e-mail nimb-j@elsevier.nl

NH
ELSEVIER
North-Holland, an imprint of Elsevier Science

Reprinted from

NIM B
Beam Interactions with Materials & Atoms

Nuclear Instruments and Methods in Physics Research B 129 (1997) 11-15

Accurate universal parameterization of absorption cross sections II — neutron absorption cross sections

R.K. Tripathi [a,*], John W. Wilson [b], Francis A. Cucinotta [b]

[a] Hampton University, Hampton, VA 23669, USA
[b] NASA Langley Research Center, Hampton, VA 23681, USA

Received 25 October 1996; revised form received 3 December 1996

ELSEVIER

BEAM INTERACTIONS WITH MATERIALS AND ATOMS

Nuclear Instruments and Methods in Physics Research – Section B

Aims and scope

Section B of Nuclear Instruments and Methods in Physics Research (NIM B) provides a special forum for the discussion of all aspects of the interaction of energetic beams with atoms, molecules and aggregate forms of matter. This includes ion beam analysis and ion beam modification of materials, as well as studies of the basic interaction mechanisms of importance for this work. The Editors invite submission of both theoretical and experimental papers of original research in this area.

Abstracted/indexed in:

Current Contents: Engineering, Technology and Applied Sciences; EI Compendex Plus; Engineering Index; INSPEC; Physics Briefs.

Subscription information 1997

Volumes 121–133 of Nuclear Instruments and Methods in Physics Research - Section B (ISSN 0168-583X) are scheduled for publication. A combined subscription to NIM A volumes 384–401 and NIM B volumes 121–133 is available at a reduced rate.

Subscriptions are accepted on a prepaid basis only and are entered on a calendar year basis. Issues are sent by SAL (Surface Air Lifted) mail wherever this service is available. Airmail rates are available upon request. For orders, claims, product enquiries (no manuscript enquiries) please contact the Customer Support Department at the Regional Sales Office nearest to you:

New York: Elsevier Science, P.O. Box 945, New York, NY 10159-0945, USA; tel +1 212 633 3730 (Toll free number for North American customers: 1-888-4ES-INFO (437-4636)), fax +1 212 633 3680, e-mail usinfo-f@elsevier.com

Amsterdam: Elsevier Science, P.O. Box 211, 1000 AE Amsterdam, The Netherlands; tel +31 20 485 3757, fax +31 20 485 3432, e-mail nlinfo-f@elsevier.nl

Tokyo: Elsevier Science, 9-15, Higashi-Azabu 1-chome, Minato-ku, Tokyo 106, Japan; tel +81 3 5561 5033, fax +81 3 5561 5047, e-mail kyf04035@niftyserve.or.jp

Singapore: Elsevier Science, No. 1 Temasek Avenue, #17-01 Millenia Tower, Singapore 039192; tel +65 434 3727, fax +65 337 2230, e-mail asiainfo@elsevier.com.sg

Claims for issues not received should be made within six months of our publication (mailing) date.

US Mailing notice: Nuclear Instruments and Methods in Physics Research – Section B (ISSN 0168-583X) is published semi-monthly (for five months of the year), monthly from August to December, three times a month in May, and four times in April, by Elsevier Science B.V., Molenwerf 1, P.O. Box 211, 1000 AE Amsterdam, The Netherlands. Annual subscription price in the USA is US$ 6396 (valid in North, Central and South America only), including air speed delivery. Periodicals postage paid at Jamaica, NY 11431.

USA Postmasters: Send address changes to Nuclear Instruments and Methods in Physics Research – Section B, Publications Expediting, Inc., 200 Meacham Avenue, Elmont, NY 11003. Airfreight and mailing in the USA by Publications Expediting Inc.

∞ The paper used in this publication meets the requirements of ANSI/NISO Z39.48-1992 (Permanence of Paper).

Printed in The Netherlands

North-Holland, an imprint of Elsevier Science

ELSEVIER

Nuclear Instruments and Methods in Physics Research B 129 (1997) 11-15

NIM B
Beam Interactions with Materials & Atoms

Accurate universal parameterization of absorption cross sections II — neutron absorption cross sections

R.K. Tripathi [a,*], John W. Wilson [b], Francis A. Cucinotta [b]

[a] Hampton University, Hampton, VA 23669, USA
[b] NASA Langley Research Center, Hampton, VA 23681, USA

Received 25 October 1996; revised form received 3 December 1996

Abstract

A recent parameterization (here after referred as paper I, Ref. [4]) of absorption cross sections for any system of charged ions collisions including proton –nucleus collisions, is extended for neutron–nucleus collisions valid from ~ 1 MeV to a few GeV, thus providing a comprehensive picture of absorption cross sections for any system of collision pair (charged and/or uncharged). The parameters are associated with the physics of the problem. At lower energies, the optical potential at the surface is important and the Pauli operator plays an increasingly important role at intermediate energies. The agreement between the calculated and experimental data is better than earlier published results.

1. Introduction

The transport of neutrons in matter is of direct interest in several technologically important and scientific areas [1-3] including space radiations, cosmic ray propagation studies in galactic medium, nuclear power plants, radiobiological effects impacting on industrial and public health. For the proper assessment to radiation exposures both reliable transport codes and accurate input data are needed.

An important ingredient of the input data is the total absorption (reaction) cross section, defined as the total minus the elastic cross sections for two colliding ions:

$$\sigma_R = \sigma_T - \sigma_{el}. \tag{1}$$

Recently, we have developed a simple accurate formalism (paper I and Ref. [5]) for the total absorption cross sections for any system of charged colliding ions including protons. The present work extends the formalism to neutron–nucleus collisions, thus presenting a simple accurate comprehensive formalism for the absorption cross sections for any combination of colliding ions (charged and/or uncharged) valid for the entire energy range. We have retained the high energy features of the model [6] developed here at NASA Langley Research Center (LaRC) where it is accurate, and improved on its behavior at lower energies within the universal formalism recently developed (paper I and Ref. [5]). The other commonly used model [7] gives good results for higher energies but shows increasingly larger deviations from experiment for lower energies.

2. Model description

Most of the empirical models approximate total reaction cross section for charged ion collisions of Bradt–Peters form [8], but have very different form for the neutron–nucleus collisions. We have maintained the uniform consistent picture for all the systems proton–nucleus, nucleus–nucleus, and now for the neutron–nucleus collisions, and have written total reaction cross sections for neutron–nucleus collisions also of the Bradt–Peters form:

$$\sigma_R = \pi r_0^2 \left(A_P^{1/3} + A_T^{1/3} - \delta \right)^2, \tag{2}$$

where r_0 is energy independent and δ is either energy-independent or dependent parameter, and A_P and A_T are the projectile and target mass numbers respectively.

It is well known that this type of parameterization is suited for higher energies and is modified through Coulomb interaction at lower energies (paper I and Ref. [5]) for the charged ion collisions. For the neutron–nucleus collisions there is no Coulomb interaction, but the total reaction cross section, in this case, is modified by the strength of the imaginary part of the optical potential at the surface. Since we are using this form of parameterization for the neutron–nucleus case for the first time (which helps to provide the unified consistent and accurate picture for the total reaction cross sections for any system of colliding nuclei for the entire energy range), we introduce a low

* Corresponding author. Fax: +1-804-864-8094; email: rkt@hesb1.larc.nasa.gov

PII S0168-583X(97)00121-3

energy multiplier (X_m) accounting for the strength of the optical model interaction. In addition, the effects of the transparency and Pauli blocking are taken into account through the energy dependent parameter, δ_E, defined latter in the text. We, therefore, propose the following similar form for the reaction cross sections for the neutron–nucleus:

$$\sigma_R = \pi r_0^2 (A_P^{1/3} + A_T^{1/3} + \delta_E)^2 X_m, \tag{3}$$

where $r_0 = 1.1$ fm. The low energy multiplier X_m is given by

(i) For $A_T < 200$

$$X_m = 1 - X_1 \exp\left(-\frac{E}{X_1 S_L}\right), \tag{4}$$

where $S_L = 0.6$ for $A_T < 12$, $S_L = 1.6$ for $A_T = 12$, $S_L = 1$ otherwise with

$$X_1 = 2.83 - 3.1 \times 10^{-2} A_T + 1.7 \times 10^{-4} A_T^2. \tag{5}$$

For the low energy, shell effects play an important role in light nuclei and the optical potential at the surface varies differently with these effects showing variation in S_L.

(ii) For $A_T \geq 200$

$$X_m = \left[1 - 0.3\exp\left(-\frac{E-1}{15}\right)\right]\left[1 - \exp(0.9 - E)\right]. \tag{6}$$

The effects of the energy dependence at intermediate and higher energies due to Pauli blocking and transparency are taken into account in δ_E, which is defined as,

$$\delta_E = 1.85S + 0.16S/E_{CM}^{1/3} - C_E + 0.91(A_T - 2Z_T)Z_P/(A_T A_P), \tag{7}$$

where S is the mass asymmetry term and is given by

$$S = \frac{A_P^{1/3} A_T^{1/3}}{A_P^{1/3} + A_T^{1/3}} \tag{8}$$

and is related to the volume overlap of the collision system. For the results reported here $A_P = 1$. The last term on the right hand side of Eq. (7) accounts for the isotope dependence of the reaction cross section. The term C_E is related to the transparency and Pauli blocking and is given by

$$C_E = D[1 - \exp(-E/T_1)] - 0.292\exp(-E/792) \times \cos(0.229E^{0.453}), \tag{9}$$

where $T_1 = 40$ (except for $11 \leq A_T \leq 40$ a value of $T_1 = 30$ is recommended for a better fit). Here D is related to the density dependence of the colliding system and the global value is given by

$$D_g = \frac{0.538}{\rho_{A_P} + \rho_{A_T}}. \tag{10}$$

The density of a nucleus is calculated in the hard sphere model, and for a nucleus A_i is given by

$$\rho_{A_i} = A_i / \frac{4\pi}{3} r_i^3, \tag{11}$$

where r_i is the equivalent sphere radius and is related to the $r_{rms,i}$ radius by

$$r_i = 1.29 r_{rms,i}, \tag{12}$$

where $r_{rms,i}$ values are taken from the experiment [9].

There is interesting physics associated with the constant D. This in effect simulates the modifications of the reaction cross sections due to Pauli blocking. This effect is new and was introduced in our charged particles reaction cross section work (paper I), and is being used for the first time in neutron–nucleus work. This is an important physical ingredient of the model and helps present a unified picture of the reaction cross sections for any system of colliding particles.

Let us elaborate on the choice of D in Eq. (9). This has contributions from the global characteristics of nuclei and also takes into account the specific characteristics related to their stability. The density of a nucleus is a very useful global property. We, therefore, associate the global value D_g to the nuclear densities (Eq. (11)) of the colliding system. Consequently, for *most systems*, we have:

$$D = D_g, \tag{13}$$

where D_g has been defined in Eq. (10). This value of D is modified in certain groups of nuclei to account for their special features in the following way:

The shell structure plays an important role in the size of a light nucleus and hence its cross sections. These effects are more prevalent upto double closed sd shell nuclei ($A \leq 40$) and manifest themselves as a tightly bound nucleus and also as isotopic effects. Hence for this group of nuclei, by taking into account these special characteristics, the best value of D is given by:

For $A_T \leq 40$

$$D = D_g - 1.5(A_T - 2Z_T)/A_T + 0.25/\{1 + \exp[(E - 170)/100]\}. \tag{14}$$

The second term on the RHS of Eq. (14) accounts for the isotopic effects and the last energy dependent term accounts for the shell effects upto doubly closed sd shell nuclei. For still heavier nuclei shell effects start becoming less important but the isotopic effects persist on. We, therefore, found better agreement using the following expression:

For $40 < A_T < 60$

$$D = D_g - 1.5(A_T - 2Z_T)/A_T. \tag{15}$$

For even higher nuclei ($A \geq 60$) special characteristics do not dominate the stability of a nucleus and the global value of D defined in Eq. (13) works well. However, for

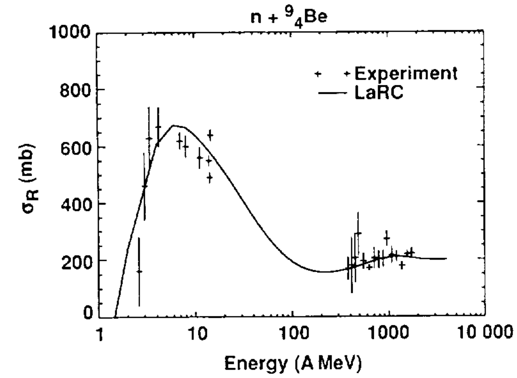


Fig. 1. Total absorption cross sections for n + $^{9}_{4}$Be as a function of neutron energy.

very heavy systems the Coulomb force becomes an important effect and manifests itself as neutron excess (or proton deficiency) for the stability of a nucleus. We found that it is necessary to modify the global value of D (Eq. 13) for nuclei heavier than lead to account for this effect. We determine that the best value of D for, $Z_T > 82$ is given by

$$D = D_g - Z_T/(A_T - Z_T). \tag{16}$$

For any regions not covered by these special effects the global value of D (Eq. (13)) gives good results.

3. Results/conclusions

Figs. 1–12 show the plot of the total absorption cross sections for the neutron–nucleus collisions. We observe that cross sections are never negative and are always positive quantities. For a particular system the energy at which the cross section drops down to zero is the lowest energy to which our model should be used. The data for

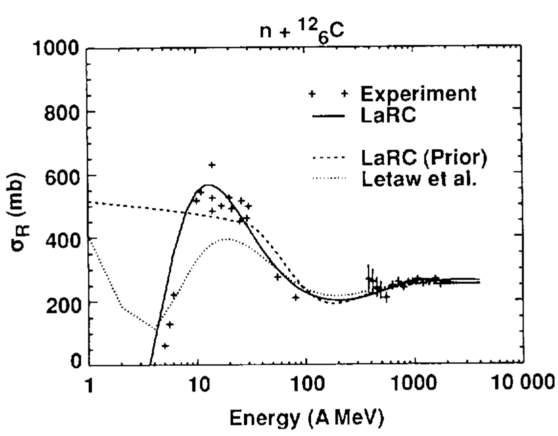


Fig. 2. Total absorption cross sections for n + $^{12}_{6}$C as a function of neutron energy.

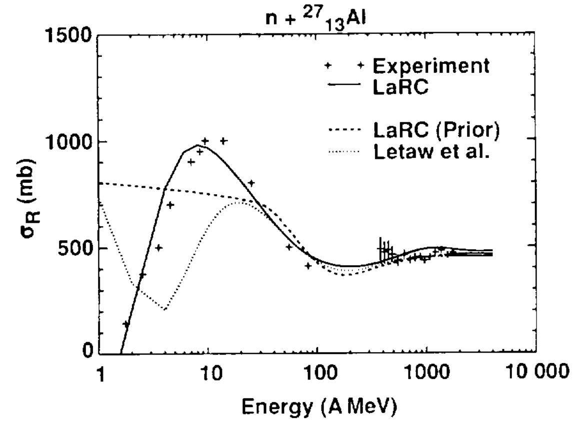


Fig. 3. Total absorption cross sections for n + $^{27}_{13}$Al as a function of neutron energy.

higher energies (379–1731 MeV) has been taken from Ref. [10], and for lower energies has been taken from the compilations of ENDF/B-VI, and Refs. [11,12].The agreement with experiment is excellent for all nuclei for the

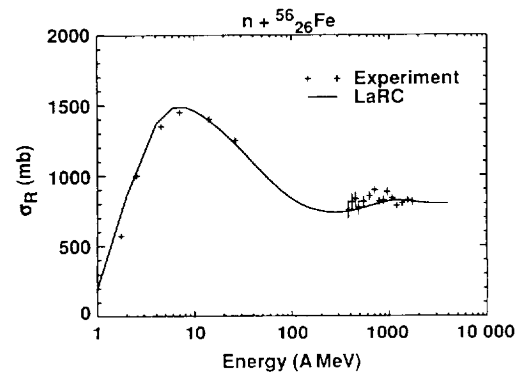


Fig. 4. Total absorption cross sections for n + $^{56}_{26}$Fe as a function of neutron energy.

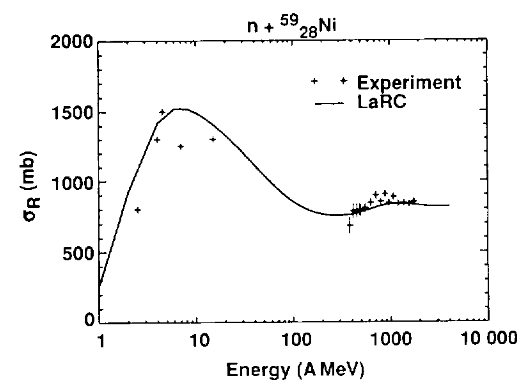


Fig. 5. Total absorption cross sections for n + $^{59}_{28}$Ni as a function of neutron energy.

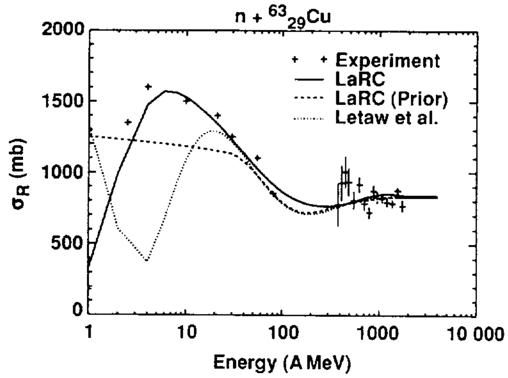


Fig. 6. Total absorption cross sections for n + $^{63}_{29}$Cu as a function of neutron energy.

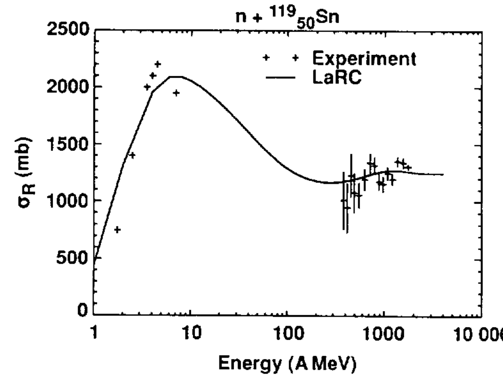


Fig. 9. Total absorption cross sections for n + $^{119}_{50}$Sn as a function of neutron energy.

entire energy range. We have also compared (Figs. 2, 3, 6, 8, 10) present results with the two popular models: model developed by Wilson et al. [6] here at the NASA Langley Research Center (LaRC (Prior)), and that of Letaw et al. [7] at the Naval Research Laboratory (NRL). We see from the plots that both these models agree very well with experiment at higher energies, however, there are depar-

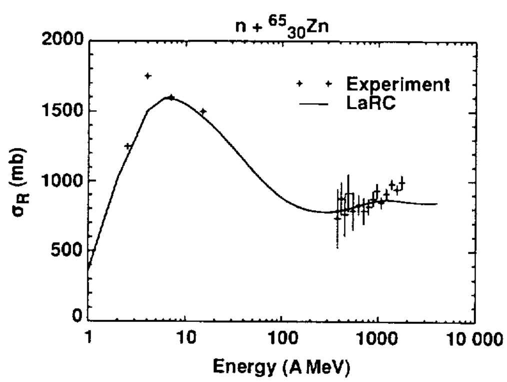


Fig. 7. Total absorption cross sections for n + $^{65}_{30}$Zn as a function of neutron energy.

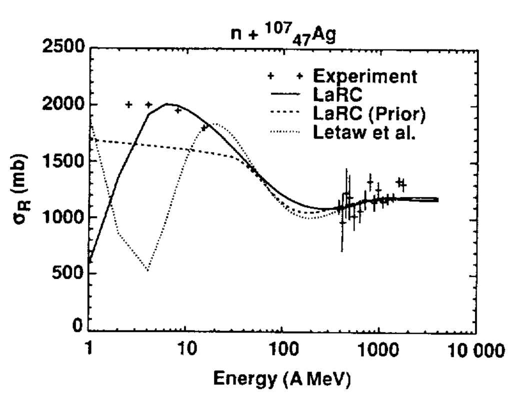


Fig. 8. Total absorption cross sections for n + $^{107}_{47}$Ag as a function of neutron energy.

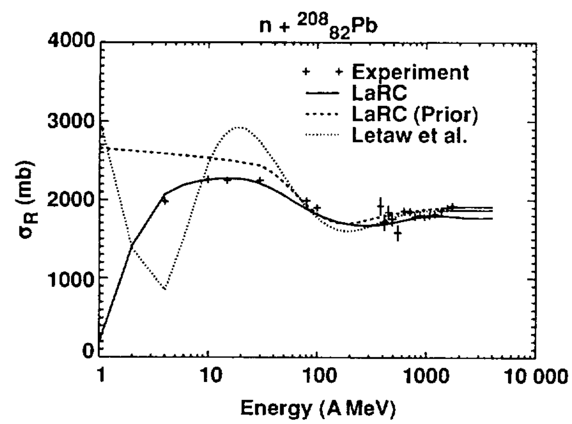


Fig. 10. Total absorption cross sections for n + $^{208}_{82}$Pb as a function of neutron energy.

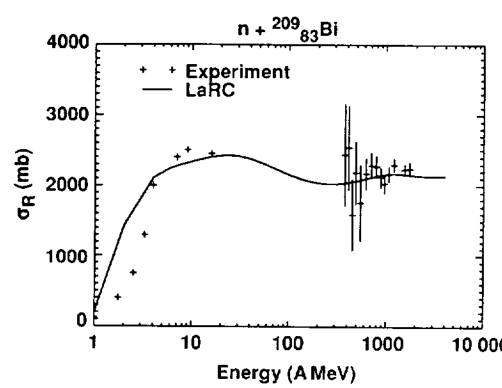


Fig. 11. Total absorption cross sections for n + $^{209}_{83}$Bi as a function of neutron energy.

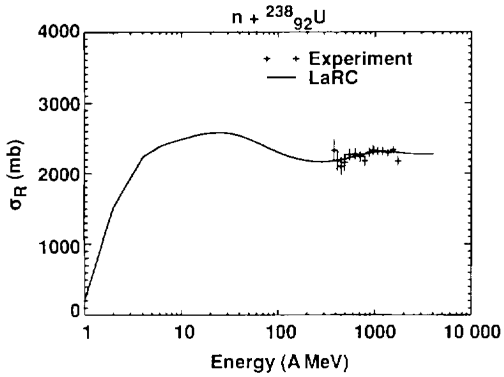


Fig. 12. Total absorption cross sections for $n + {}^{238}_{92}U$ as a function of neutron energy.

tures at lower energies. In general LaRC gives better results than NRL model at lower energies.

Clearly present model (LaRC) improves on earlier models and gives accurate results to much lower energies, and is a welcome improvement for the transport model data base. Neutrons are the dominant component of the radiation environment for the High Speed Civil Transport (HSCT) mission where the data base proposed here is of immense importance.

We have successfully presented simple accurate and unified model for the total absorption cross sections for any system of charged and/or uncharged collision systems valid for the entire energy range, which are important ingredients for several data bases including transport. The model will also be useful where analytical forms of the cross sections are needed.

In view of its utility the computer program calculating the comprehensive accurate absorption cross sections of paper I and present paper will be placed in the COSMIC program library for the public use.

Note added in proof

There is an error in Eq. (12) of paper I (Ref. [4]). A pair of parentheses is missing. The correct equation should read as follows:

$$D = 2.77 - 8.0 \times 10^{-3} A_T + 1.8 \times 10^{-5} A_T^2 - 0.8/(1 + \exp((250 - E)/75)). \qquad (12)$$

Acknowledgements

One of the authors (RKT) acknowledges NASA Langley Research Center for the support.

References

[1] J.W. Wilson et al., NASA R.P.- 1257 (December 1991).
[2] K.Z. Morgan and J.E. Turner, Principles of Radiation Protection (Wiley, New York, 1967).
[3] M. Eisenbud, Environmental Radioactivity, 2nd Ed. (Academic Press, New York, 1973).
[4] R.K. Tripathi, F.A. Cucinotta, J.W. Wilson, Nucl. Instr. and Meth. B 117 (1966) 347.
[5] R.K. Tripathi, F.A. Cucinotta and J.W. Wilson, NASA TP 3621 (1997).
[6] J.W. Wilson, L.W. Townsend, W.W. Buck, S.Y. Chun, B.S. Hong and S.L. Lamkin, NASA TM 4053 (1988).
[7] J.R. Letaw, R. Silberberg, C.H. Tsao, Astrophys. J. Suppl 51 (1983) 271.
[8] H.L. Bradt, B. Peters, Phys. Rev. 77 (1977) 54.
[9] H. DeVries, C.W. DeJager, C. DeVries, Atom. Data Nucl. Data Tabl. 36 (1987) 495.
[10] W. Schimmerling, T.J. Devlin, W.W. Johnson, K.G. Vosburg, R.E. Mischka, Phys. Rev. 7 (1973) 248.
[11] V. McLane, C.L. Dunford and P.F. Rose, Neutron Cross Sections, Vol. 2 (Academic Press, New York, 1988).
[12] D.J. Hughes and R.B. Schwartz, Neutron Cross Sections, BNL-325, 2nd Ed. (Brookhaven National Lab., 1958).

Instructions to Authors

Submission of papers

Contributions should be submitted to one of the Editors (see inside front cover). It is suggested that manuscripts originating from Europe, India, The Middle East and Africa be sent to Prof. H.H. Andersen, and from The Americas, The Far East and Australasia, to Dr. L.E. Rehn.
Manuscript and figures should be submitted in duplicate, with one set of good quality figure material for production of the printed figures. If possible, please submit also an electronic version of your contribution on diskette.
Short contributions of less than 1500 words and not subdivided into sections may be published as Letters to the Editor in a shorter time than regular articles as the proofs will normally be corrected by the Publisher.
Submission of a manuscript implies that it is not being considered for publication elsewhere and that the authors have obtained the necessary authority for publication.

Manuscript preparation

Manuscripts should be written in good English. They should be typed throughout with double line spacing and wide margins on numbered, single column pages. See notes opposite on electronic manuscripts.
Structure. Please adhere to the following order of presentation: article title, author(s), affiliations, abstract, PACS codes and keywords, main text, acknowledgements, appendices, references, figure captions, tables.
Corresponding author. The name, full postal address, telephone and fax numbers and e-mail address of the corresponding author should be given on the first page.
Classification codes/keywords. Please supply one to four classification codes (PACS and/or MSC), and up to six keywords of your own choice that describe the content of your article in more detail.
References to other publications should be numbered consecutively within square brackets and listed together at the end of the text. In the case of multiple authorship all authors should be listed in the references; only in case of more than ten authors is the first author et al. acceptable.

Illustrations

The Publisher requires a set of good quality drawings and original photographs to produce the printed figures.
Line drawings should be 1.5–3 times larger than the printed size; the height of letters and numbers should, after reduction, fall within the range 1.2–2.4 mm. Do not use too narrow pen widths for machine-plotted graphs. Shaded areas should be shown by means of cross-hatching or a matrix of dots, rather than a continuous grey wash.
Photographs should not already be screened (overprinted with the point matrix used by printers). The top side of a photograph should be marked if necessary.
Colour figures can be printed in colour when this is essential to the presentation. Authors will be charged for colour reproduction. Further information can be obtained from the Publisher.

After acceptance

Notification. You will be notified by the Editor of the acceptance of your contribution, and invited to send an electronic file of the accepted version to the Publisher, if this is not yet available. After acceptance any correspondence should be addressed to the Publisher at the coordinates below.
Page proofs are sent out to the Author in order to check that no undetected errors have arisen in the typesetting or file conversion process. In the proofs only typesetting errors may be corrected. No changes in, or additions to, the accepted paper will be accepted.
Copyright transfer. In the course of the production process the authors will be asked to transfer the copyright of the article to the publisher. This transfer will ensure the widest possible dissemination of information.

Electronic manuscripts

If possible, an electronic version of the manuscript should be submitted on a diskette together with the hard copies of the text and figures, or should be sent (after acceptance) by e-mail or on a diskette to the Publisher. It is the responsibility of the Author to ensure that the electronic version exactly matches the hard copy. No deviations from the version accepted for publication are permissible without the prior and explicit approval by the Editor. Such changes should be clearly indicated on an accompanying print-out of the file.
LaTeX articles and articles prepared with any of the well known word processors can be handled by the Publisher. Further information can be obtained from the Publisher.

Author benefits

No page charges. Publishing in Nuclear Instruments and Methods in Physics Research – Section B is free.
Free offprints. The corresponding author will receive 50 offprints free of charge. An offprint order form will be supplied by the publisher for ordering any additional paid offprints.
Discount. Contributors to Elsevier Science journals are entitled to a 30% discount on all Elsevier Science books.

Correspondence with the Publisher

After acceptance of an article any correspondence should be addressed to Elsevier Science B.V., NIM-B, P.O. Box 2759, 1000 CT Amsterdam, The Netherlands
Tel. +31 20 485 2500, fax +31 20 485 2431
e-mail nimb-j@elsevier.nl

North-Holland, an imprint of Elsevier Science

NASA Technical Paper 3621

Universal Parameterization of Absorption Cross Sections

R. K. Tripathi
Southern Illinois University • Carbondale, Illinois

Francis A. Cucinotta and John W. Wilson
Langley Research Center • Hampton, Virginia

National Aeronautics and Space Administration
Langley Research Center • Hampton, Virginia 23681-0001

January 1997

Available electronically at the following URL address: http://techreports.larc.nasa.gov/ltrs/ltrs.html

Printed copies available from the following:

NASA Center for AeroSpace Information
800 Elkridge Landing Road
Linthicum Heights, MD 21090-2934
(301) 621-0390

National Technical Information Service (NTIS)
5285 Port Royal Road
Springfield, VA 22161-2171
(703) 487-4650

Abstract

This paper presents a simple universal parameterization of total reaction cross sections for any system of colliding nuclei that is valid for the entire energy range from a few AMeV to a few AGeV. The universal picture presented here treats proton-nucleus collision as a special case of nucleus-nucleus collision, where the projectile has charge and mass number of one. The parameters are associated with the physics of the collision system. In general terms, Coulomb interaction modifies cross sections at lower energies, and the effects of Pauli blocking are important at higher energies. The agreement between the calculated and experimental data is better than all earlier published results.

Introduction

Transportation of energetic ions in bulk matter is of direct interest in several areas (ref. 1), including shielding against ions originating from either space radiations or terrestrial accelerators, cosmic ray propagation studies in a galactic medium, or radiobiological effects resulting from the workplace or clinical exposures. For carcinogenesis, terrestrial radiation therapy, and radiobiological research, knowledge of the beam composition and interactions is necessary to properly evaluate the effects on human and animal tissues. For proper assessment of radiation exposures, both reliable transport codes and accurate input parameters are needed.

One such important input is the total reaction (σ_R) cross section, defined as the total (σ_T) minus the elastic (σ_{el}) cross sections for two colliding ions:

$$\sigma_R = \sigma_T - \sigma_{el} \tag{1}$$

In view of its importance, the total reaction cross section has been extensively studied both theoretically (refs. 1–14) and experimentally (refs. 15–24) for the past five decades. A detailed list of references is given in references 1, 13, and 16. Empirical prescriptions have been developed (refs. 2–4, 10, 11, and 13) for the total reaction cross sections working in various energy ranges and combination of interacting ions. The present model works in all energy ranges with uniform accuracy for any combination of interacting ions, including proton-nucleus collisions, and is more accurate than earlier reported empirical models (ref. 10), which were accurate above 100 AMeV but showed large errors up to 25 percent at lower energies.

Model Description

Most of the empirical models approximate the total reaction cross section of Bradt-Peters form with

$$\sigma_R = \pi r_0^2 \left(A_P^{1/3} + A_T^{1/3} - \delta\right)^2 \tag{2}$$

where r_0 is energy-independent, δ is either an energy-independent or energy-dependent parameter, and A_P and A_T are the projectile and target mass numbers, respectively. This form of parameterization works nicely for higher energies. However, for lower energies, Coulomb interaction becomes important and modifies reaction cross sections significantly. In addition, strong absorption models suggest energy dependence of the interaction radius. Incorporating these effects, and other effects discussed later in the text, we propose the following form for the reaction cross section:

$$\sigma_R = \pi r_0^2\left(A_P^{1/3} + A_T^{1/3} + \delta_E\right)^2\left(1 - \frac{B}{E_{cm}}\right) \tag{3}$$

where $r_0 = 1.1$ fm, and E_{cm} is the colliding system center of mass energy in MeV. The last term in equation (3) is the Coulomb interaction term, which modifies the cross section at lower energies and becomes less important as the energy increases (typically after several tens of AMeV). In equation (3), B is the energy-dependent Coulomb interaction barrier (factor on right side of eq. (3)) and is given by

$$B = \frac{1.44 Z_P Z_T}{R} \tag{4}$$

where Z_P and Z_T are the atomic numbers of the projectile and target, respectively, and R, the distance for evaluating the Coulomb barrier height, is

$$R = r_P + r_T + \frac{1.2\left(A_P^{1/3} + A_T^{1/3}\right)}{E_{cm}^{1/3}} \tag{5}$$

where r_i is equivalent sphere radius and is related to the $r_{rms,i}$ radius by

$$r_i = 1.29 r_{rms,i} \tag{6}$$

with $(i = P,T)$.

The energy dependence in the reaction cross section at intermediate and higher energies results mainly from two effects—transparency and Pauli blocking. This energy dependence is taken into account in δ_E, which is given by

$$\delta_E = 1.85S + \left(0.16S/E_{cm}^{1/3}\right) - C_E + [0.91(A_T - 2Z_T)Z_P/(A_T A_P)] \quad (7)$$

where S is the mass asymmetry term given by

$$S = \frac{A_P^{1/3} A_T^{1/3}}{A_P^{1/3} + A_T^{1/3}} \quad (8)$$

and is related to the volume overlap of the collision system. The last term on the right side of equation (7) accounts for the isotope dependence of the reaction cross section. The term C_E is related to both the transparency and Pauli blocking and is given by

$$C_E = D[1 - \exp(-E/40)] - 0.292\exp(-E/792) \times \cos\left(0.229E^{0.453}\right) \quad (9)$$

where the collision kinetic energy E is in units of AMeV. Here, D is related to the density dependence of the colliding system, scaled with respect to the density of the $^{12}C + ^{12}C$ colliding system:

$$D = 1.75\frac{\rho_{A_P} + \rho_{A_T}}{\rho_{A_C} + \rho_{A_C}} \quad (10)$$

The density of a nucleus is calculated in the hard-sphere model. Important physics is associated with constant D. In effect, D simulates the modifications of the reaction cross sections caused by Pauli blocking. The Pauli blocking effect, which has not been taken into account in other empirical calculations, is being introduced here for the first time. Introduction of the Pauli blocking effect helps present a universal picture of the reaction cross sections.

At lower energies (below several tens of AMeV) where the overlap of interacting nuclei is small (and where the Coulomb interaction modifies the reaction cross sections significantly), the modifications of the cross sections caused by Pauli blocking are small and gradually play an increasing role as the energy increases, which leads to higher densities where Pauli blocking becomes increasingly important. Interestingly enough, for the proton-nucleus case, because there is not much compression effect, a single constant value of $D = 2.05$ gives very good results for all proton-nucleus collisions. For alpha-nucleus collisions, where there is a little compression, the best value of D is given by

$$D = 2.77 - \left(8.0 \times 10^{-3} A_T\right) + \left(1.8 \times 10^{-5} A_T^2\right) - 0.8/\{1 + \exp[(250 - E)/75]\} \quad (11)$$

For lithium nuclei, because of the "halos" (ref. 21), compression is less; therefore, the Pauli blocking effect is less important. A reduced value of $D/3$ gives better results for the reaction cross sections at the intermediate and higher energies.

There are no adjustable parameters in the model except that, for proton-nucleus collisions, this method of calculating the Coulomb interaction barrier underestimates its value for the very light closed-shell nuclei of alpha and carbon, which are very tightly bound and, therefore, compact. Consequently, for these two cases, the Coulomb barrier should be increased by a factor of 27 and 3.5, respectively, for a better fit.

Results and Conclusions

Figures 1–45 show the plots of available results for proton-nucleus, alpha-nucleus, and nucleus-nucleus collisions. Figures 6 and 18 also show comparisons with reference 10. The data set used for figures 1–5 was collected from references 15 and 23 and, for figures 6–14, was obtained from references 16, 17, 22, and 23. Extensive data available for a C + C system (fig. 18) were taken from references 16, 17, 23, and 24. For the remaining figures, data were collected from the compilation of data sets from references 9 and 16–20. The agreement with experiment is excellent and is better than all other empirical models reported earlier, which is particularly important in view of the fact that the agreement is excellent throughout the whole energy range—up to a few AGeV. We notice, again, that at the lower energy end, the cross sections are modified by the Coulomb interaction, and at the intermediate and high energy end, Pauli blocking effects become increasingly important. It will be interesting to see how the model compares with the new experimental data as and when these become available.

NASA Langley Research Center
Hampton, VA 23681-0001
December 17, 1996

References

1. Wilson, John W.; Townsend, Lawrence W.; Schimmerling, Walter; Khandelwal, Govind S.; Khan, Ferdous; Nealy, John E.; Cucinotta, Francis A.; Simonsen, Lisa C.; Shinn, Judy L.; and Norbury, John W.: *Transport Methods and Interactions for Space Radiations.* NASA RP-1257, 1992.

2. Bass, Reiner: *Nuclear Reactions With Heavy Ions.* Springer-Verlag, 1980.

3. Bradt, H. L.; and Peters, B.: The Heavy Nuclei of the Primary Cosmic Radiation. *Phys. Rev.*, second ser., vol. 77, no. 1, Jan. 1, 1950, pp. 54–70.

4. Karol, Paul J.: Nucleus-Nucleus Reaction Cross Sections at High Energies: Soft-Spheres Model. *Phys. Rev. C*, vol. 11, no. 4, Apr. 1975, pp. 1203–1209.

5. Glauber, R. J.: *High-Energy Collision Theory. Lectures in Theoretical Physics, Volume I,* Wesley E. Brittin and Lita G. Dunham, eds., Interscience Publ., Inc., 1959, pp. 315–414.

6. Wilson, John W.: Composite Particle Reaction Theory. Ph.D. Diss., College of William and Mary, June 1975.

7. Wilson, J. W.; and Townsend, L. W.: An Optical Model for Composite Nuclear Scattering. *Canadian J. Phys.*, vol. 59, no. 11, 1981, pp. 1569–1576.

8. Ernst, David J.: Total Reaction Cross Sections and the Matter Density of Finite Nuclei. *Phys. Rev. C,* vol. 19, no. 3, Mar. 1979, pp. 896–904.

9. Gupta, S. K.; and Shukla, P.: Trajectory Modifications in the Glauber Model for Heavy Ions. *Phys. Rev. C*, vol. 52, no. 6, Dec. 1995, pp. 3212–3216 and references.

10. Townsend, L. W.; and Wilson, J. W.: Energy-Dependent Parameterization of Heavy-Ion Absorption Cross Sections. *Radiat. Res.*, vol. 106, 1986, pp. 283–287.

11. Shen, Wen-Qing; Wang, Bing; Feng, Jun; Zhan, Wen-Long; Zhu, Yong-Tai; and Feg, En-Pu: Total Reaction Cross Section for Heavy-Ion Collisions and Its Relation to the Neutron Excess Degree of Freedom. *Nucl. Phys.*, vol. A491, 1989, pp. 130–146.

12. Vitturi, A.; and Zardi, F.: Modified Glauber Model for the Description of Elastic Scattering Between Heavy Ions. *Phys. Rev. C*, vol. 36, no. 4, Oct. 1987, pp. 1404–1407.

13. Sihver, L.; Tsao, C. H.; Silberberg, R.; Kanai, T.; and Barghouty, A. F.: Total Reaction and Partial Cross Section Calculations in Proton-Nucleus ($Z_t \leq 26$) and Nucleus-Nucleus Reactions (Z_p and $Z_t \leq 26$). *Phys. Rev. C*, vol. 47, no. 3, Mar. 1993, pp. 1225–1236.

14. DeVries, R. M.; and Peng, J. C.: Nucleus-Nucleus Total Reaction Cross Sections. *Phys. Rev. C*, vol. 22, no. 3, Sept. 1980, pp. 1055–1064.

15. Bauhoff, W.: Tables of Reaction and Total Cross Sections for Proton-Nucleus Scattering Below 1 GeV. *At. Data & Nucl. Data Tables*, vol. 35, 1986, pp. 429–447.

16. Kox, S.; Gamp, A.; Perrin, C.; Arvieux, J.; Bertholet, R.; Bruandet, J. F.; Buenerd, M.; Cherkaoui, R.; Cole, A. J.; El-Masri, Y.; Longequeue, N.; Menet, J.; Merchex, F.; and Viano, J. B.: Trends of Total Reaction Cross Sections for Heavy Ion Collisions in the Intermediate Energy Range. *Phys. Rev. C*, vol. 35, no. 5, May 1987, pp. 1678–1691.

17. Barashenkov, V. S.; Gudima, K. K.; and Toneev, V. D.: Cross Sections for Fast Particles and Atomic Nuclei. *Prog. Phys.*, vol. 17, no. 10, 1969, pp. 683–725.

18. Webber, W. R.; Kish, J. C.; and Schrier, D. A.: Formula for Calculating Partial Cross Sections for Nuclear Reactions of Nuclei With $E \geq 200$ MeV/Nucleon in Hydrogen Targets. *Phys. Rev. C*, vol. 41, no. 2, Feb. 1990, pp. 566–571.

19. Dubar, L. V.; Eleukenov, D. Sh.; Slyusarenko, L. I.; and Yurkuts, N. P.: Parametrization of Total Cross Sections of Reactions in the Intermediate Energy Region. *Sov. J. Nucl. Phys.*, vol. 49, no. 5, May 1989, pp. 771–773.

20. Menet, J. J. H.; Gross, E. E.; Malanify, J. J.; and Zucker, A.: Total-Reaction-Cross-Section Measurements for 30-60 MeV Protons and the Imaginary Optical Potential. *Phys. Rev. C*, no. 4, Oct. 1971, pp. 1114–1129.

21. Riisager, K.: Nuclear Halo States. *Rev. Mod. Phys.*, vol. 66, no. 3, July 1994, pp. 1105–1116.

22. Auce, A.; Carlson, R. F.; Cox, A. J.; Ingemarsson, A.; Johansson, R.; Renberg, P. U.; Sundberg, O.; and Tibell, G.: Reaction Cross Sections for 75–190 MeV Alpha Particles on Targets From ^{12}C to ^{208}Pb. *Phys. Rev. C*, vol. 50, no. 2, Aug. 1994, pp. 871–879.

23. Jaros, J.; Wagner, A.; Anderson, L.; Chamberlain, O.; Fuzesy, R. Z.; Gallup, J.; Gorn, W.; Schroeder, L.; Shannon, S.; Shapiro, G.; and Steiner, H.: Nucleus-Nucleus Total Cross Sections for Light Nuclei at 1.55 and 2.89 GeV/*c* Per Nucleon. *Phys. Rev. C*, vol. 18, 1978, pp. 2273–2292.

24. Heckman, H. H.; Greiner, D. E.; Lindstrom, P. J.; and Shwe, H.: Fragmentation of ^4He, ^{12}C, ^{14}N, and ^{16}O Nuclei in Nuclear Emulsion at 2.1 GeV/Nucleon. *Phys. Rev. C*, vol. 17, no. 5, May 1978, pp. 1735–1747.

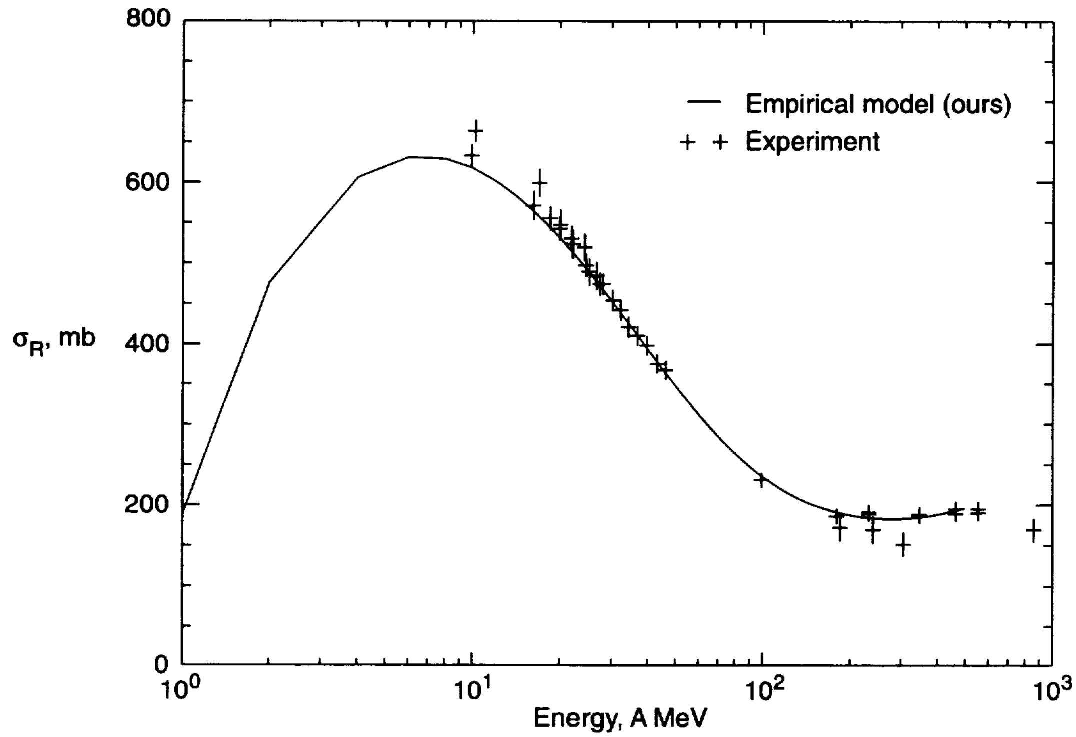


Figure 1. Reaction cross sections as a function of energy for $p + {}^{9}_{4}Be$ collisions.

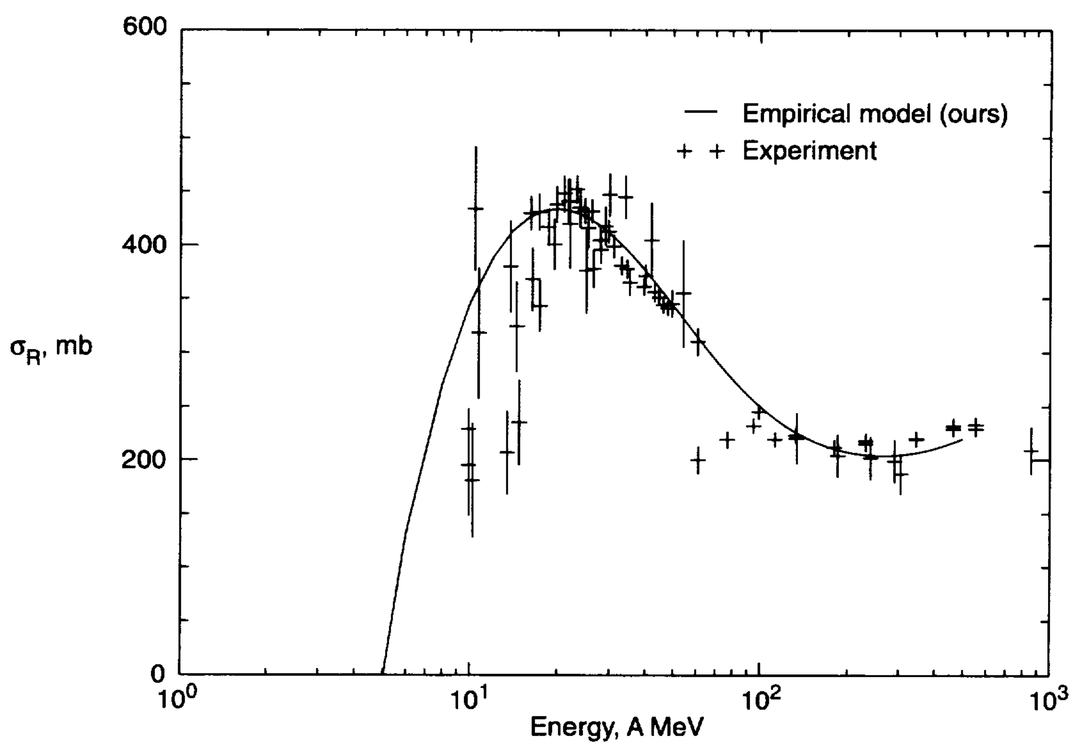


Figure 2. Reaction cross sections as a function of energy for $p + {}^{12}_{6}C$ collisions.

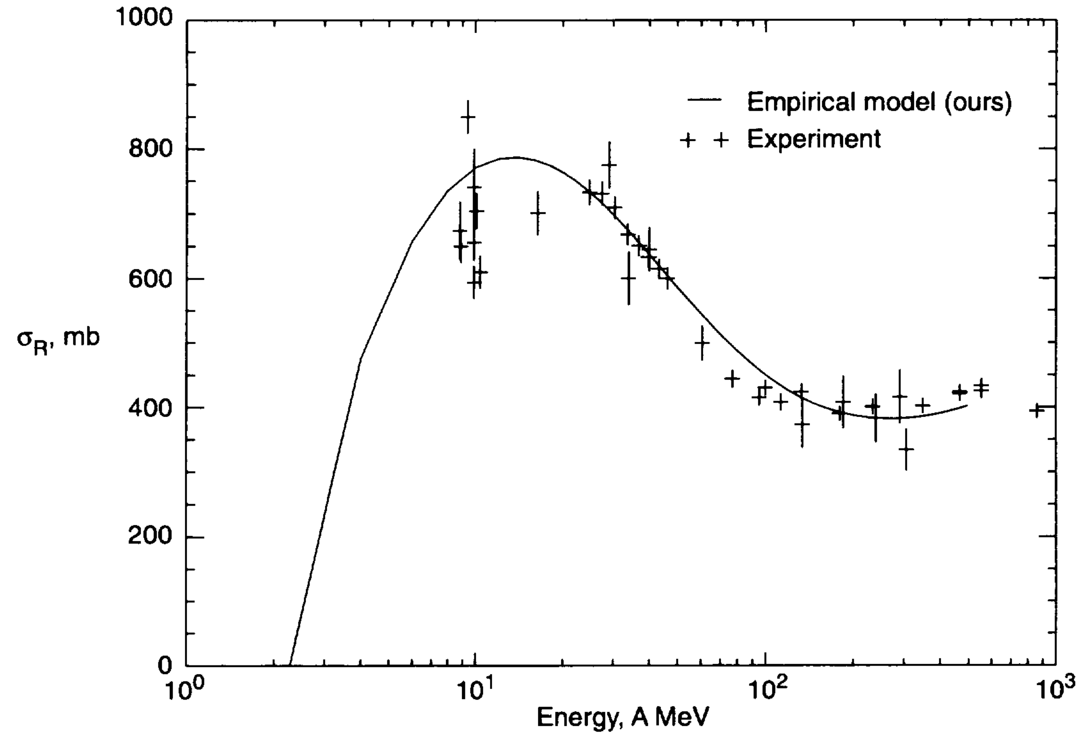


Figure 3. Reaction cross sections as a function of energy for $p + {}^{27}_{13}\mathrm{Al}$ collisions.

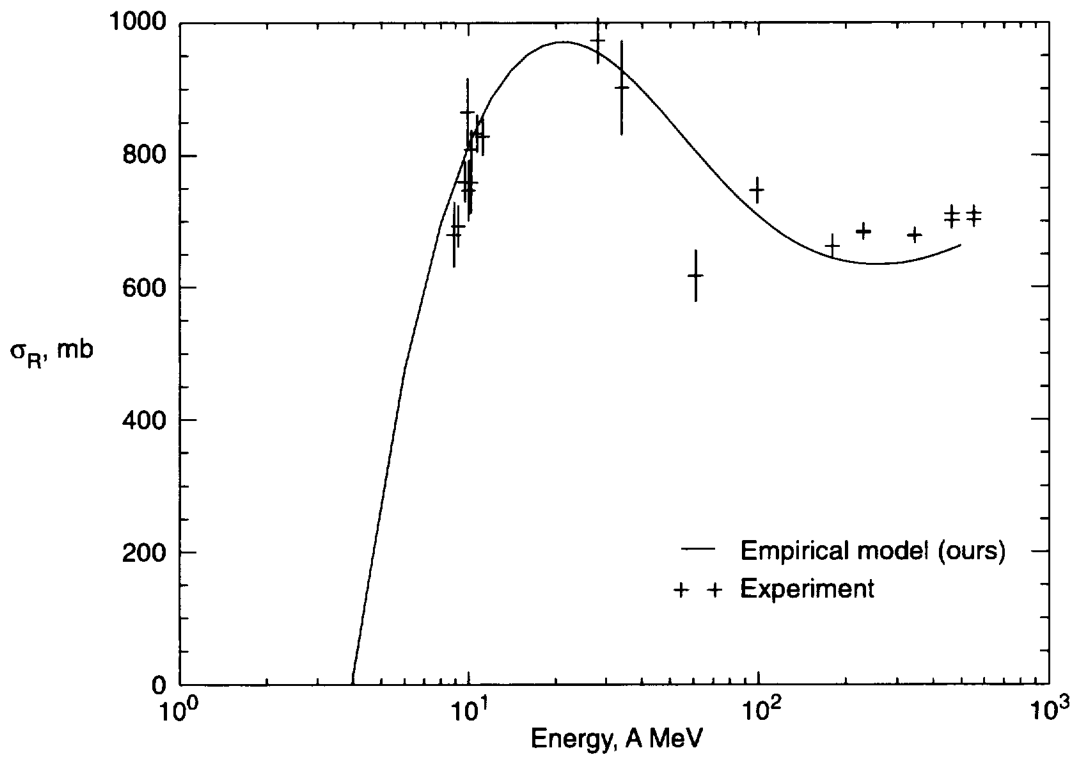


Figure 4. Reaction cross sections as a function of energy for $p + {}^{\mathrm{nat}}_{26}\mathrm{Fe}$ collisions.

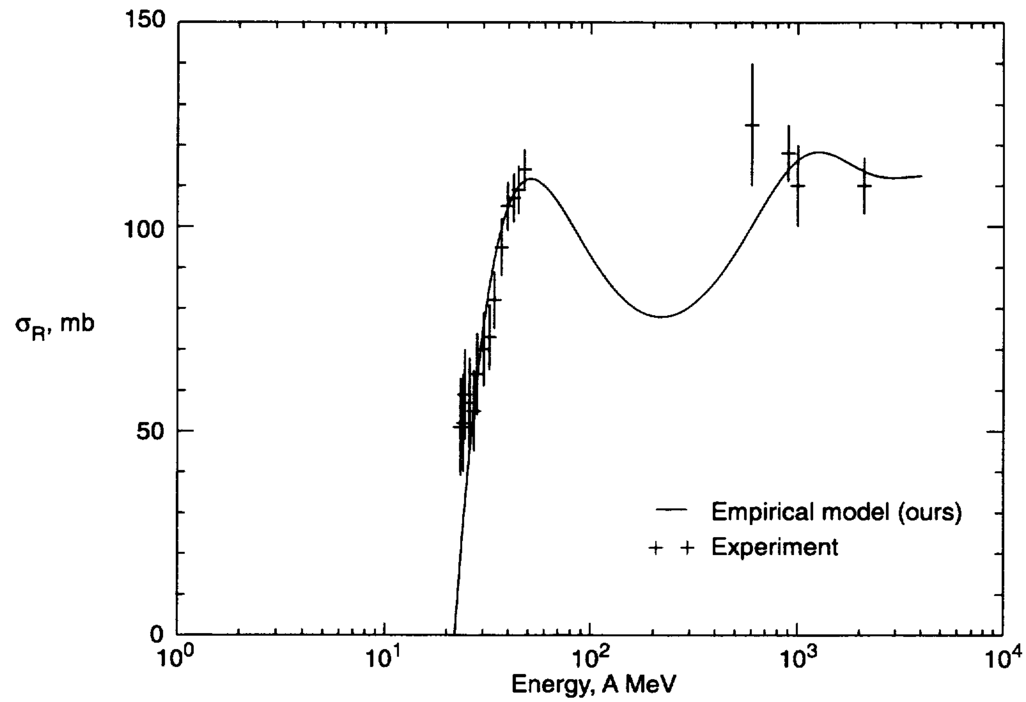


Figure 5. Reaction cross sections as a function of energy for $\alpha + {}^{1}_{1}\mathrm{H}$ collisions.

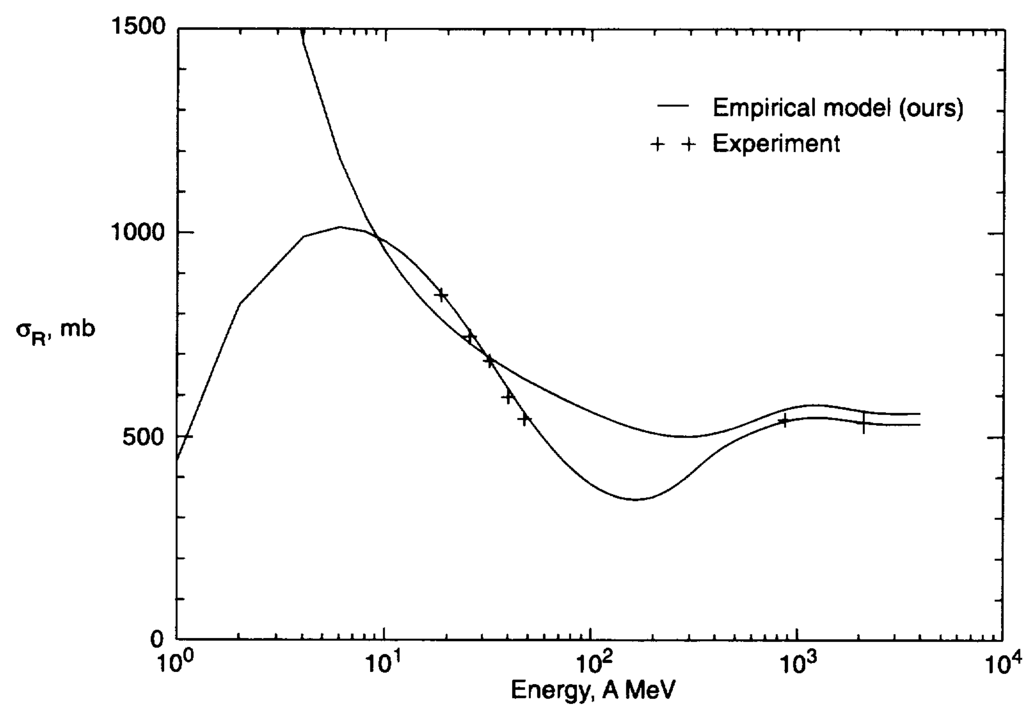


Figure 6. Reaction cross sections as a function of energy for $\alpha + {}^{12}_{6}\mathrm{C}$ collisions; dashed line is from reference 10.

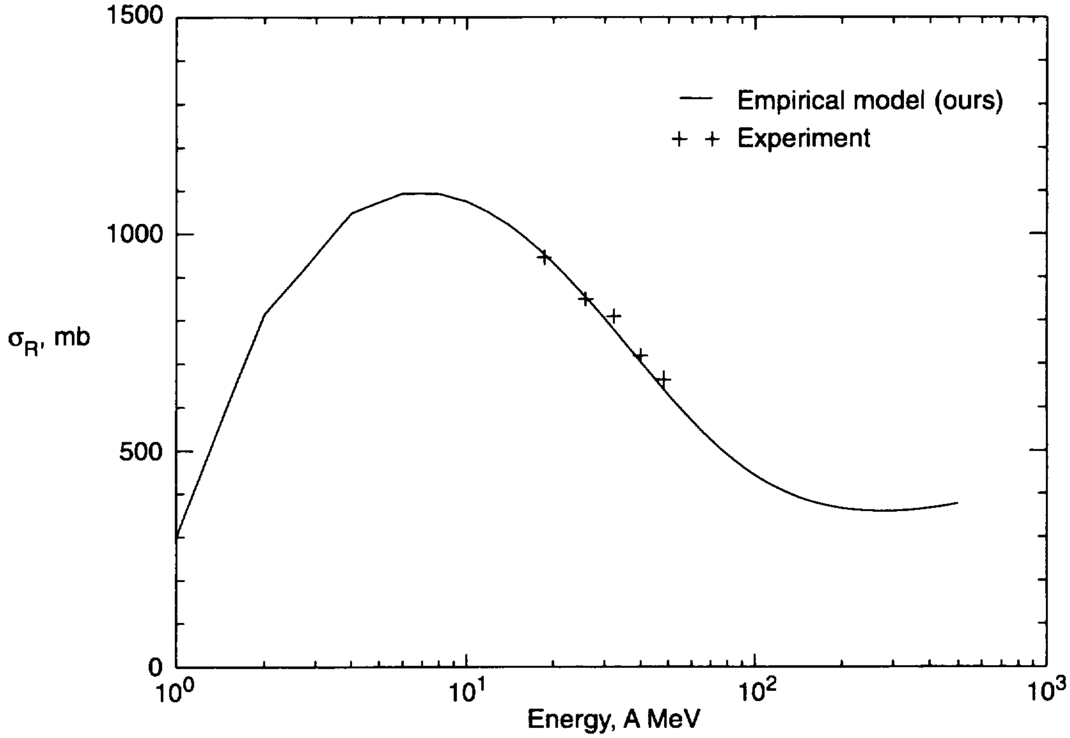


Figure 7. Reaction cross sections as a function of energy for $\alpha + {}^{16}_{8}O$ collisions.

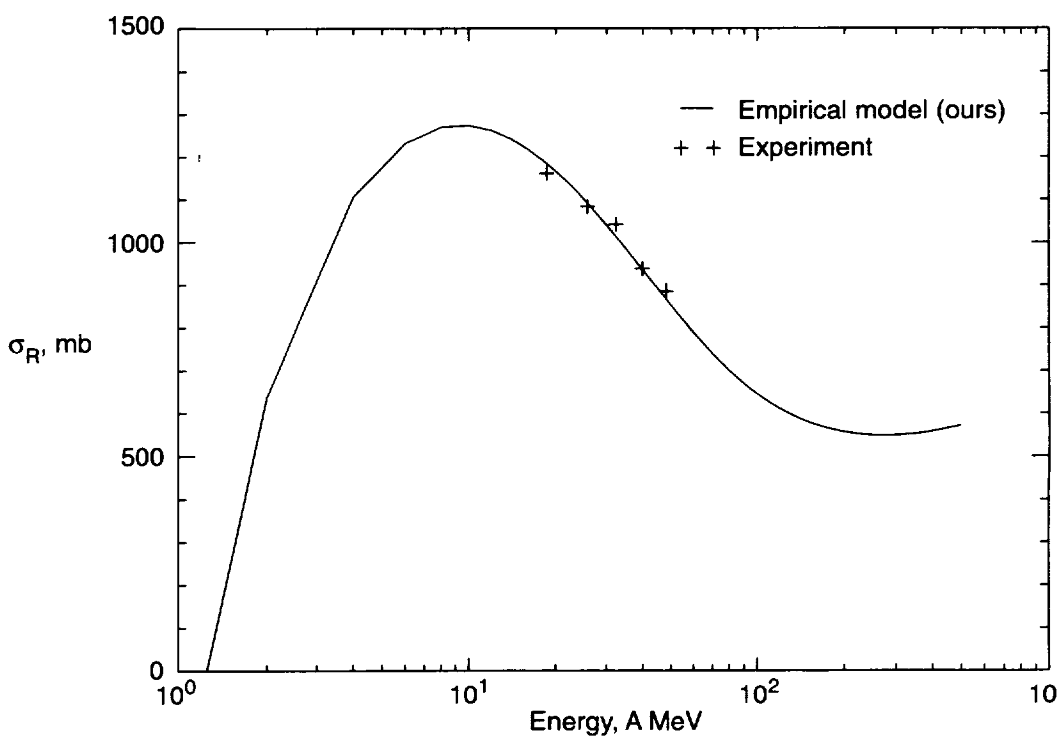


Figure 8. Reaction cross sections as a function of energy for $\alpha + {}^{28}_{14}Si$ collisions.

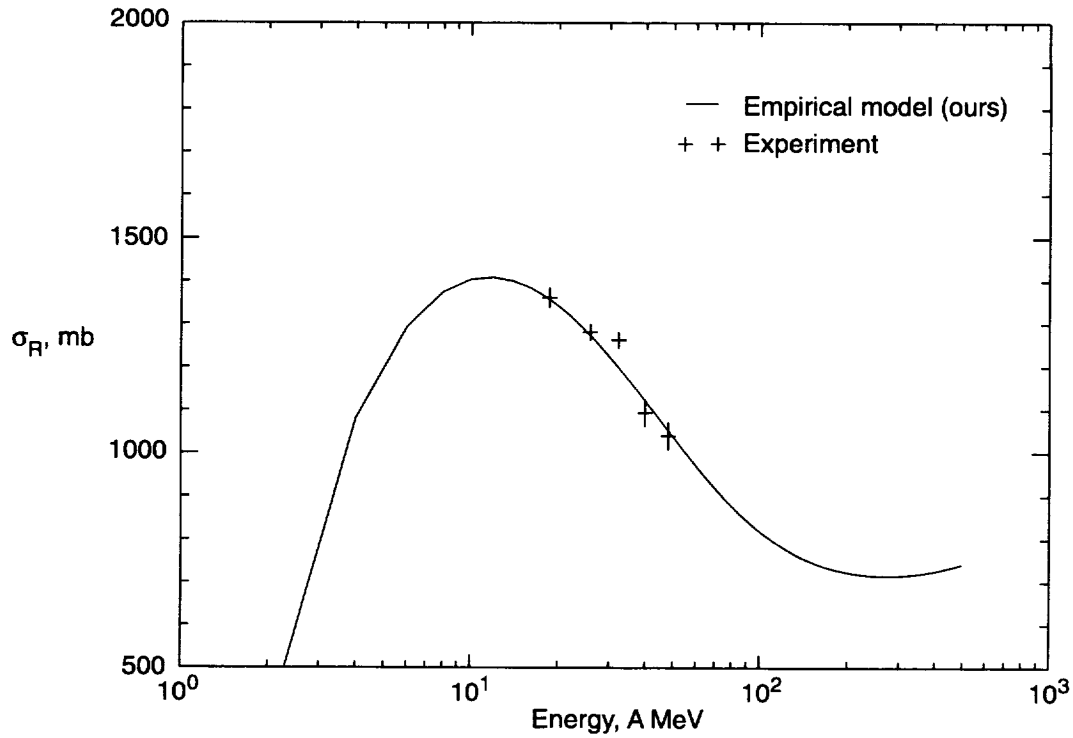


Figure 9. Reaction cross sections as a function of energy for $\alpha + {}^{40}_{20}\mathrm{Ca}$ collisions.

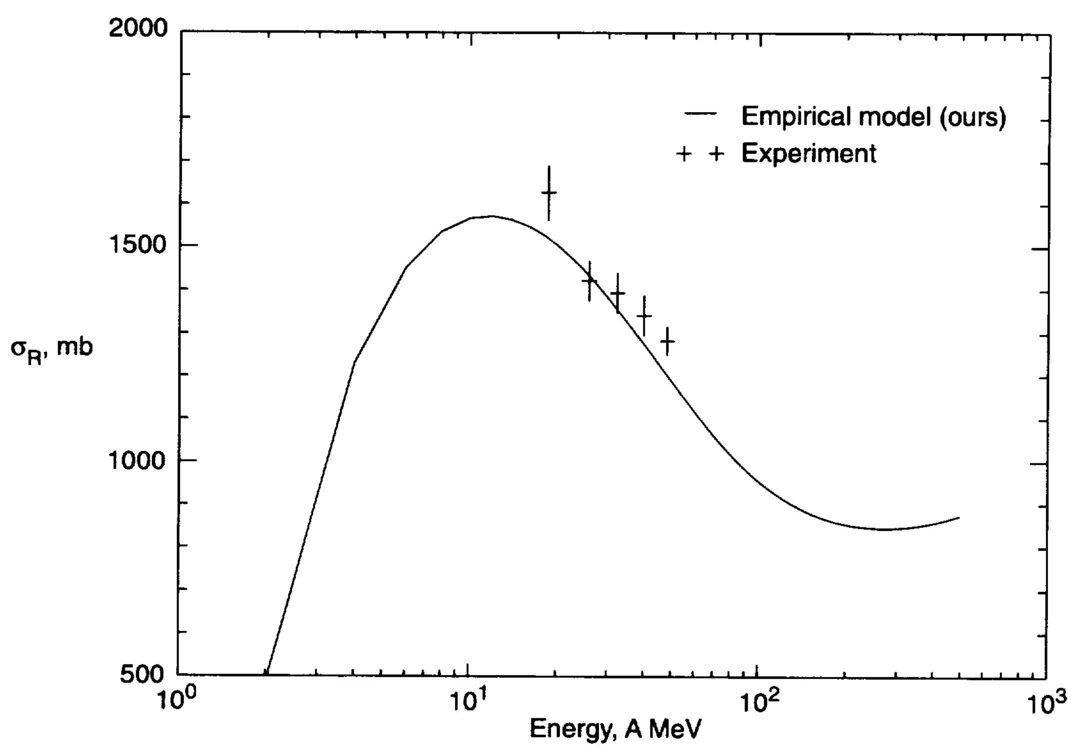


Figure 10. Reaction cross sections as a function of energy for $\alpha + {}^{48}_{20}\mathrm{Ca}$ collisions.

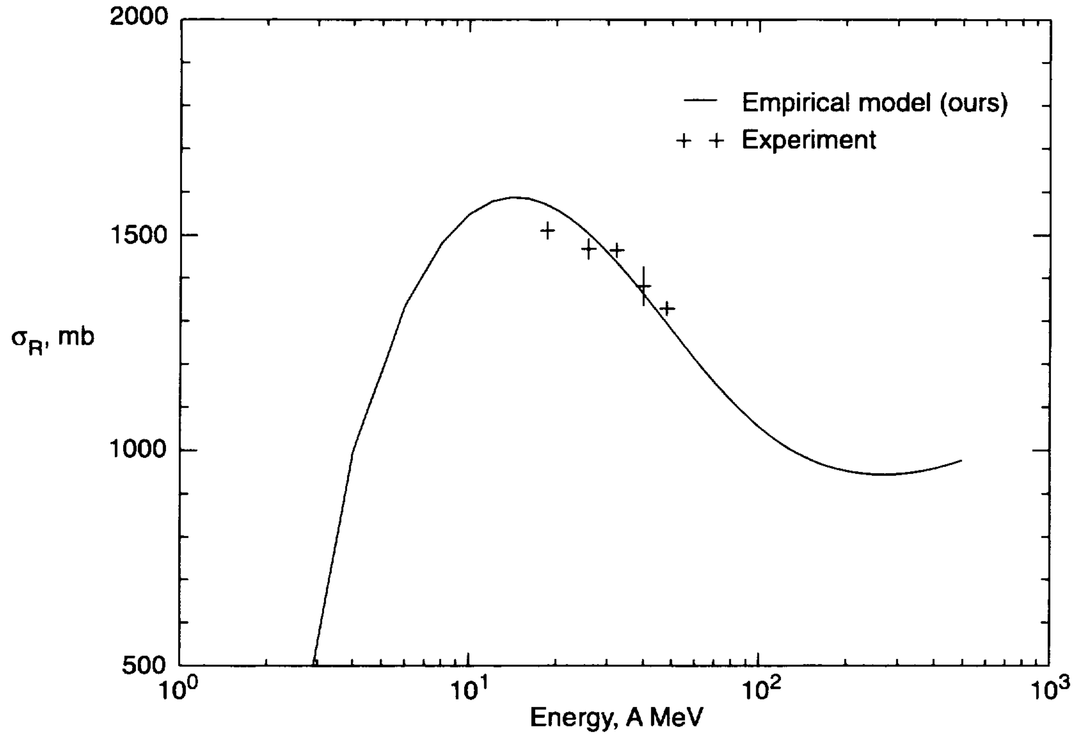


Figure 11. Reaction cross sections as a function of energy for $\alpha + {}^{58}_{28}Ni$ collisions.

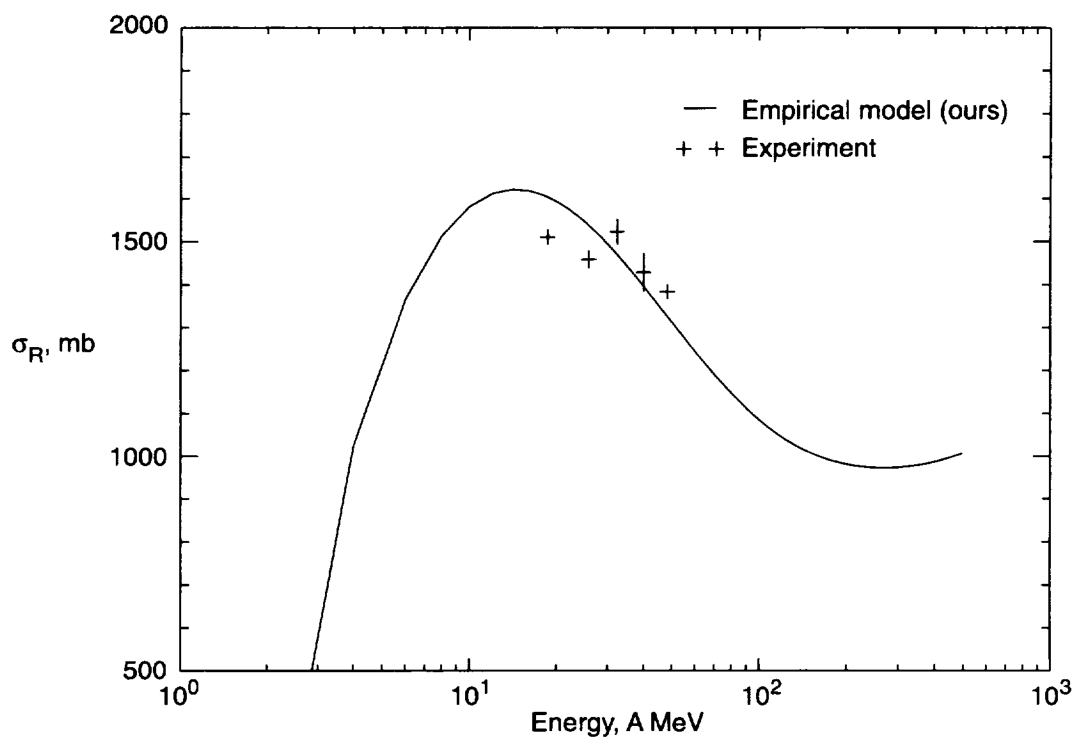


Figure 12. Reaction cross sections as a function of energy for $\alpha + {}^{60}_{28}Ni$ collisions.

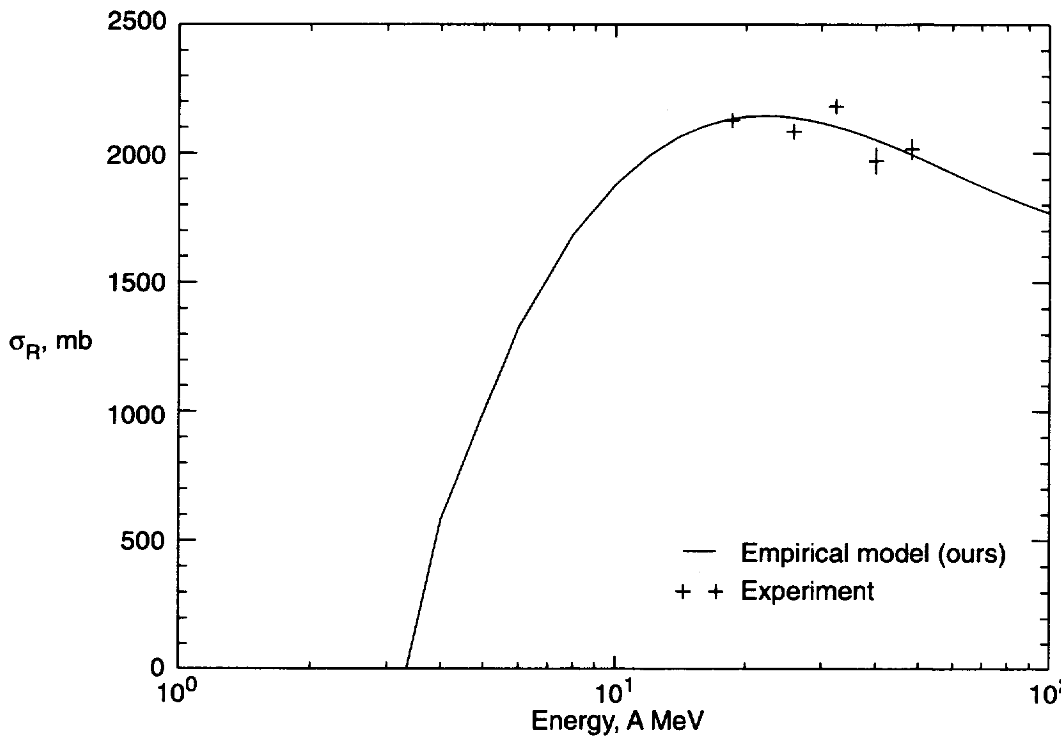


Figure 13. Reaction cross sections as a function of energy for $\alpha + {}^{124}_{50}Sn$ collisions.

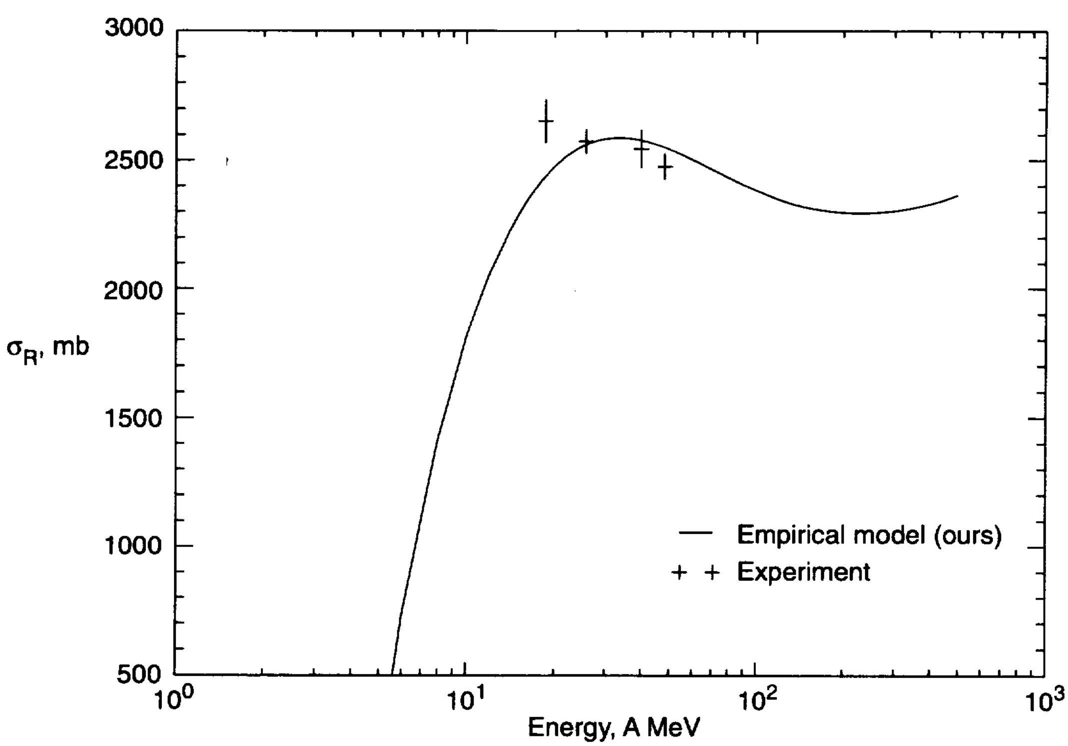


Figure 14. Reaction cross sections as a function of energy for $\alpha + {}^{208}_{82}Pb$ collisions.

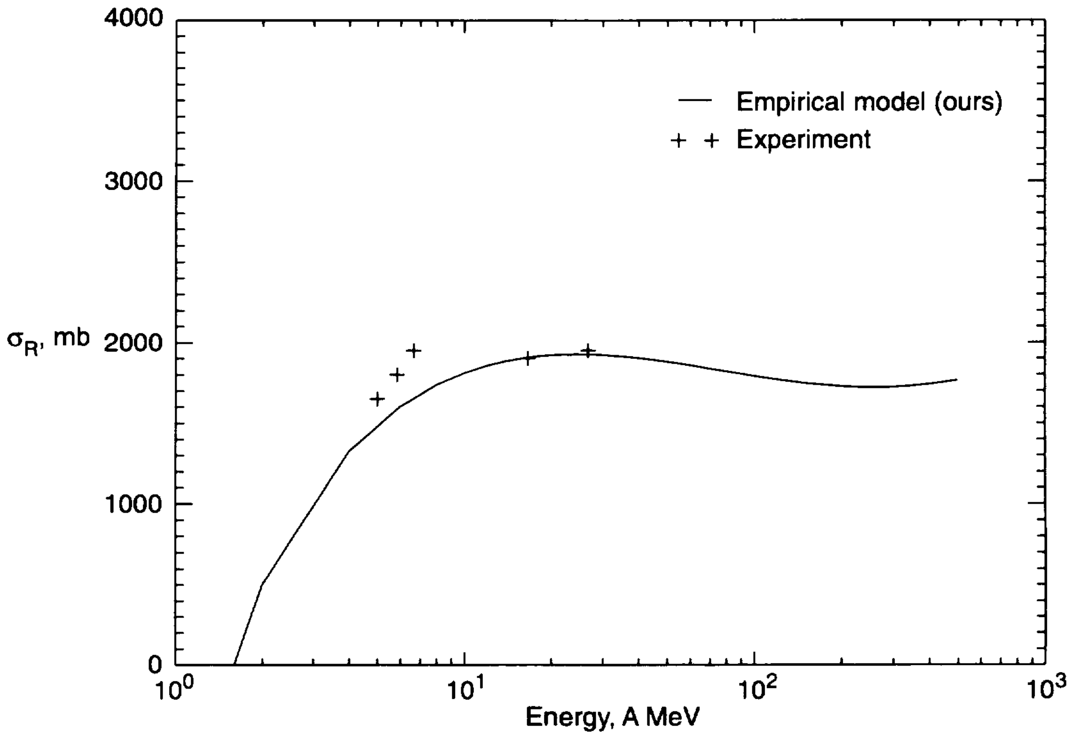


Figure 15. Reaction cross sections as a function of energy for ${}^{6}_{3}Li + {}^{40}_{20}Ca$ collisions.

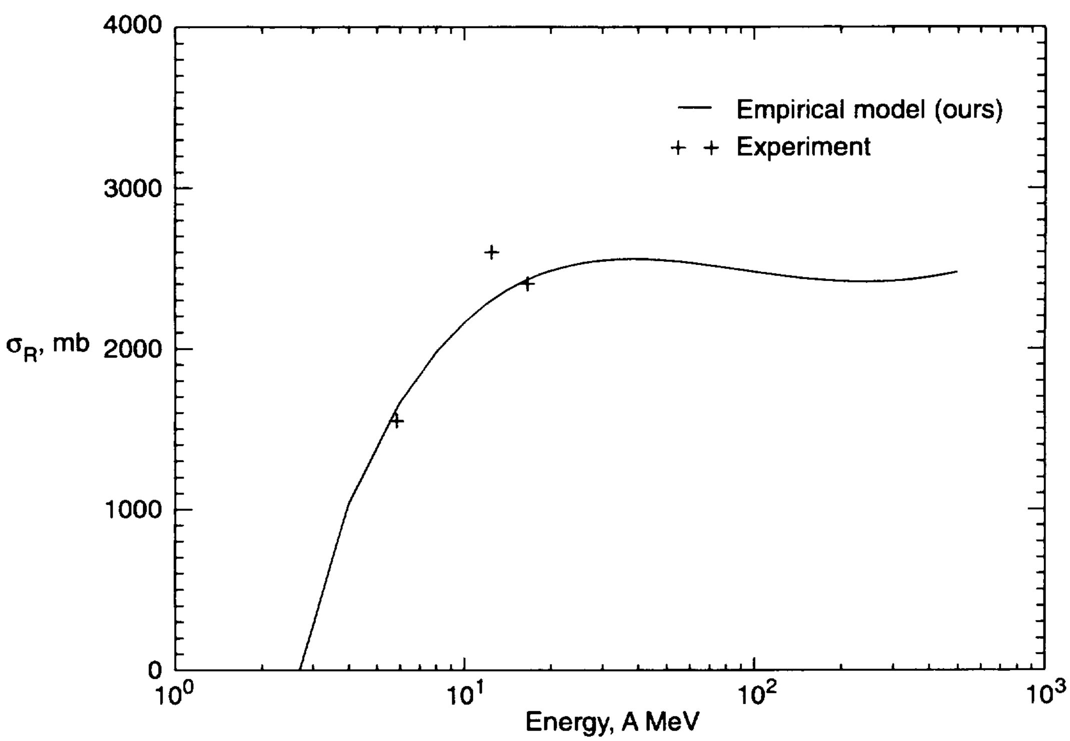


Figure 16. Reaction cross sections as a function of energy for ${}^{6}_{3}Li + {}^{90}_{40}Zr$ collisions.

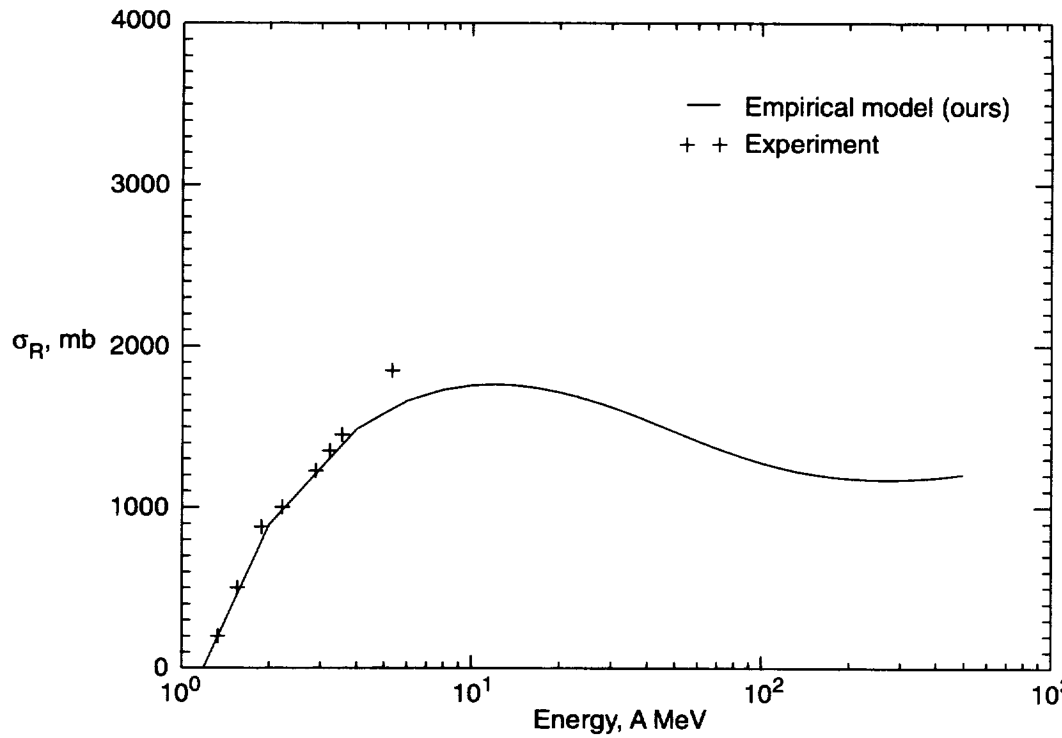


Figure 17. Reaction cross sections as a function of energy for ${}^{9}_{4}Be + {}^{28}_{14}Si$ collisions.

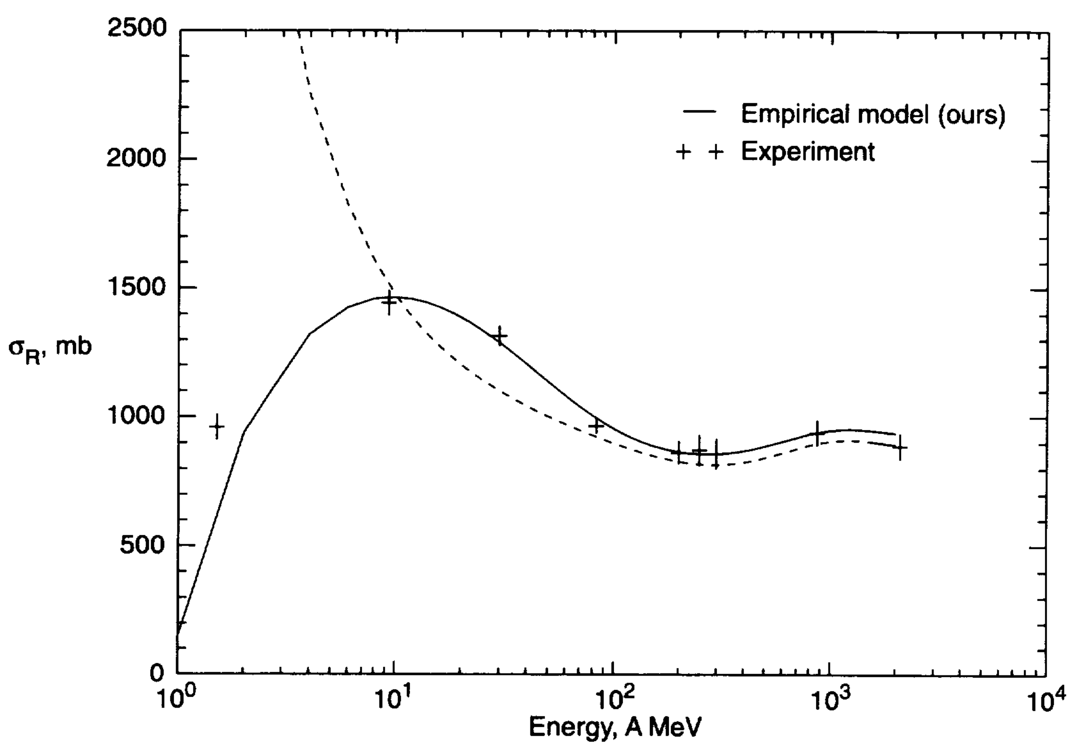


Figure 18. Reaction cross sections as a function of energy for ${}^{12}_{6}C + {}^{12}_{6}C$ collisions; dashed line is from reference 18.

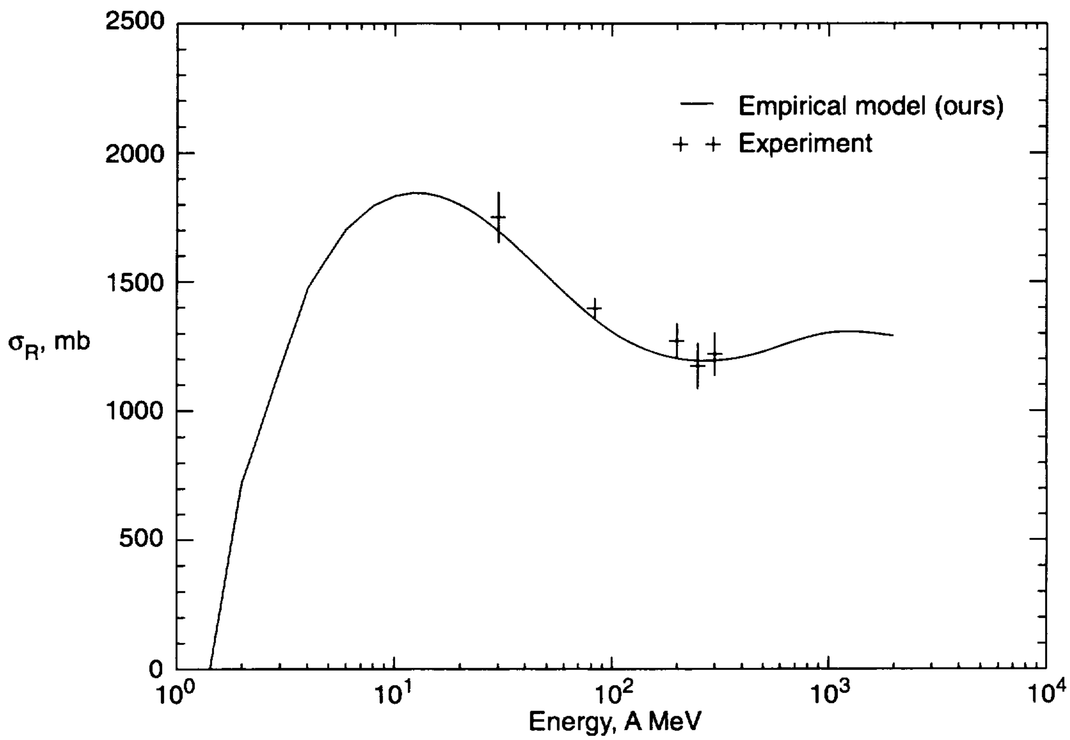


Figure 19. Reaction cross sections as a function of energy for ${}^{12}_{6}C + {}^{27}_{13}Al$ collisions.

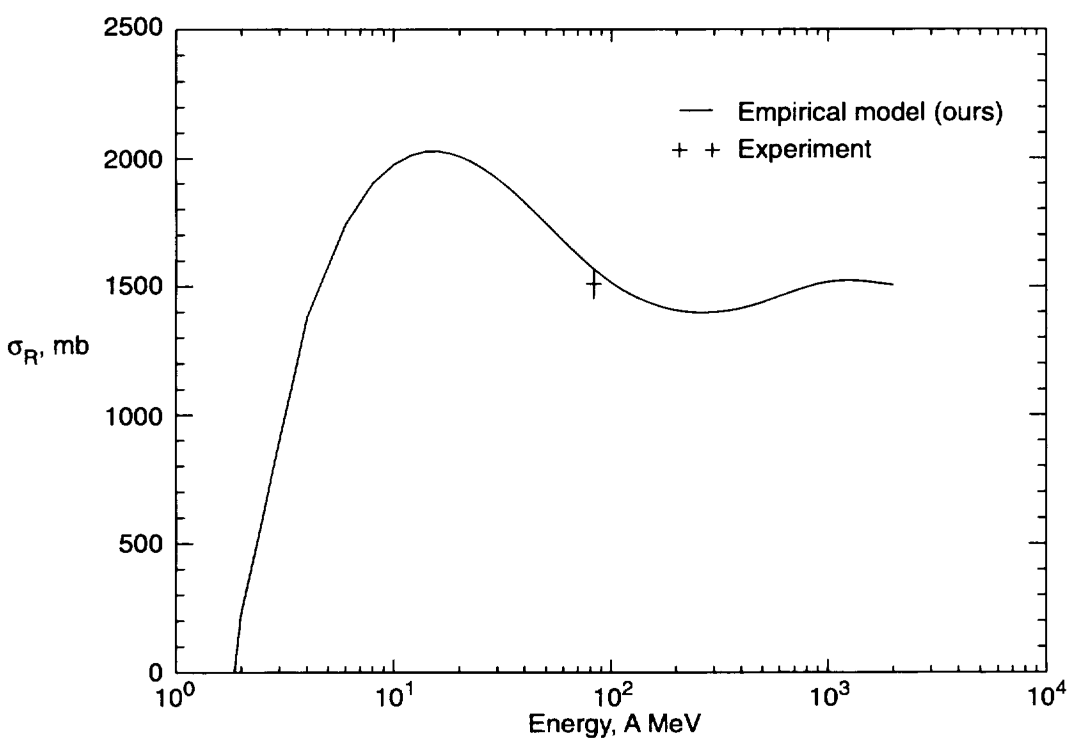


Figure 20. Reaction cross sections as a function of energy for ${}^{12}_{6}C + {}^{40}_{20}Ca$ collisions.

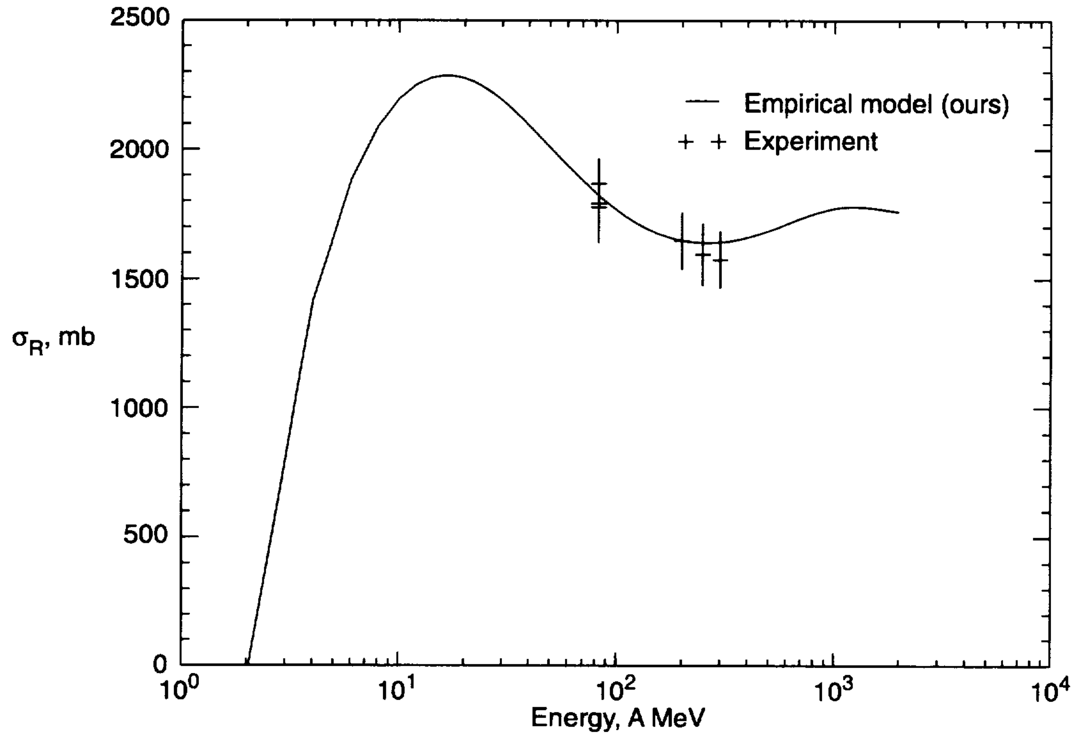


Figure 21. Reaction cross sections as a function of energy for ${}^{12}_{6}C + {}^{56}_{26}Fe$ collisions.

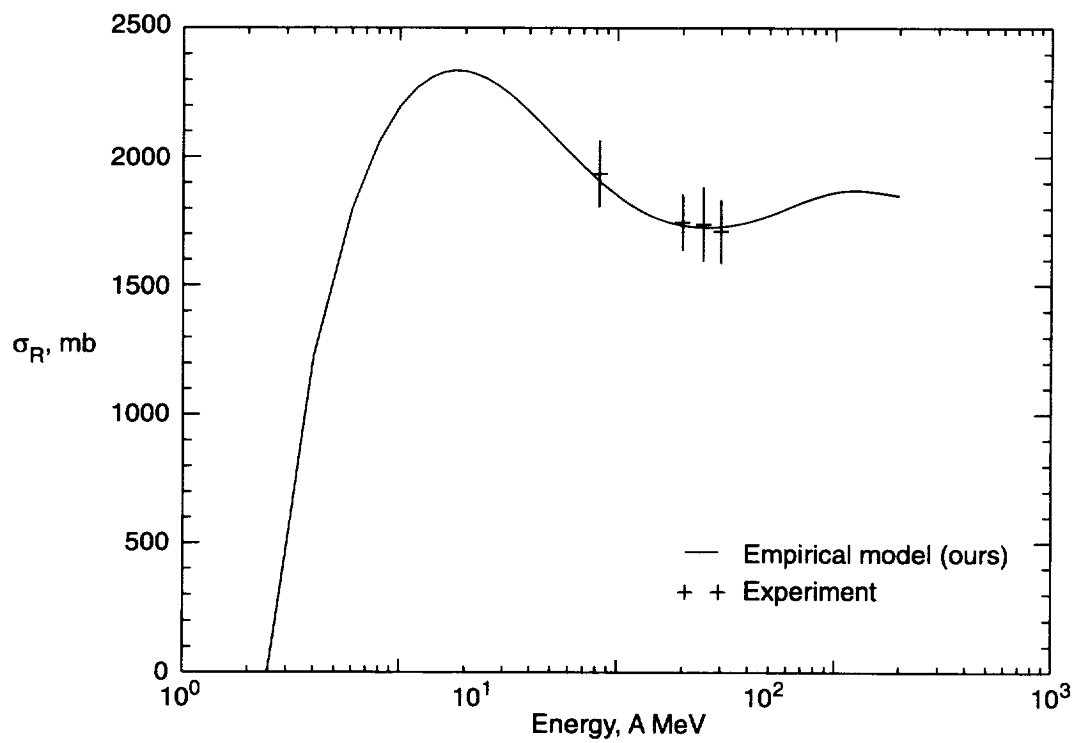


Figure 22. Reaction cross sections as a function of energy for ${}^{12}_{6}C + {}^{64}_{30}Zn$ collisions.

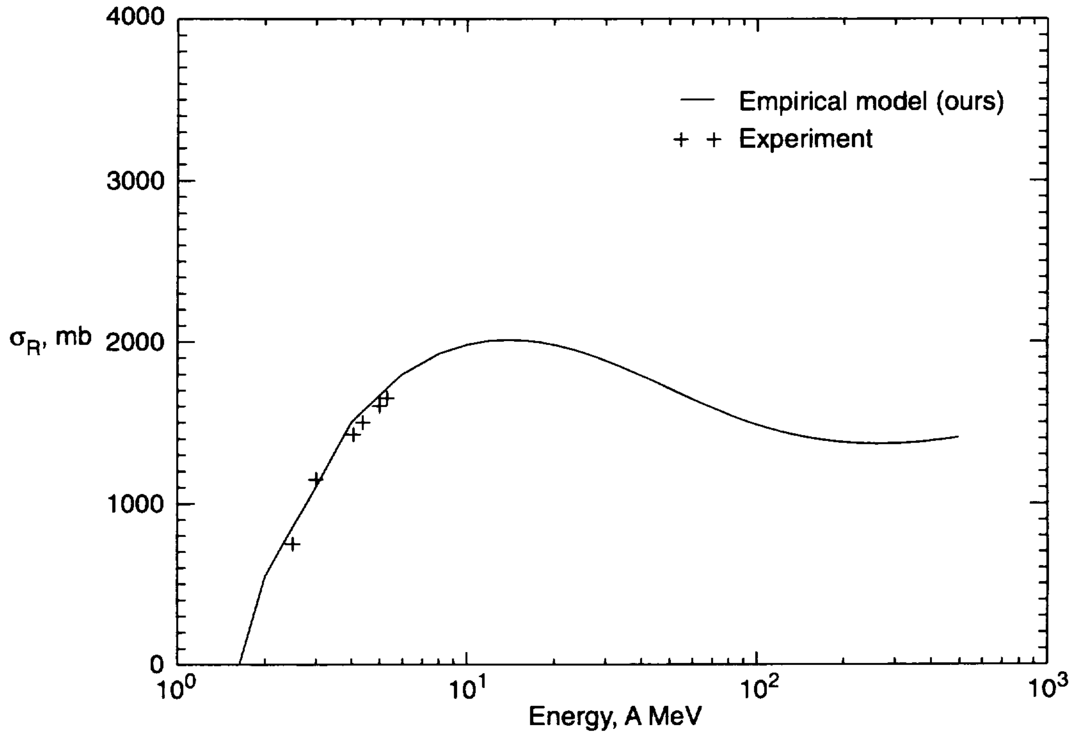


Figure 23. Reaction cross sections as a function of energy for ${}^{16}_{8}O + {}^{28}_{14}Si$ collisions.

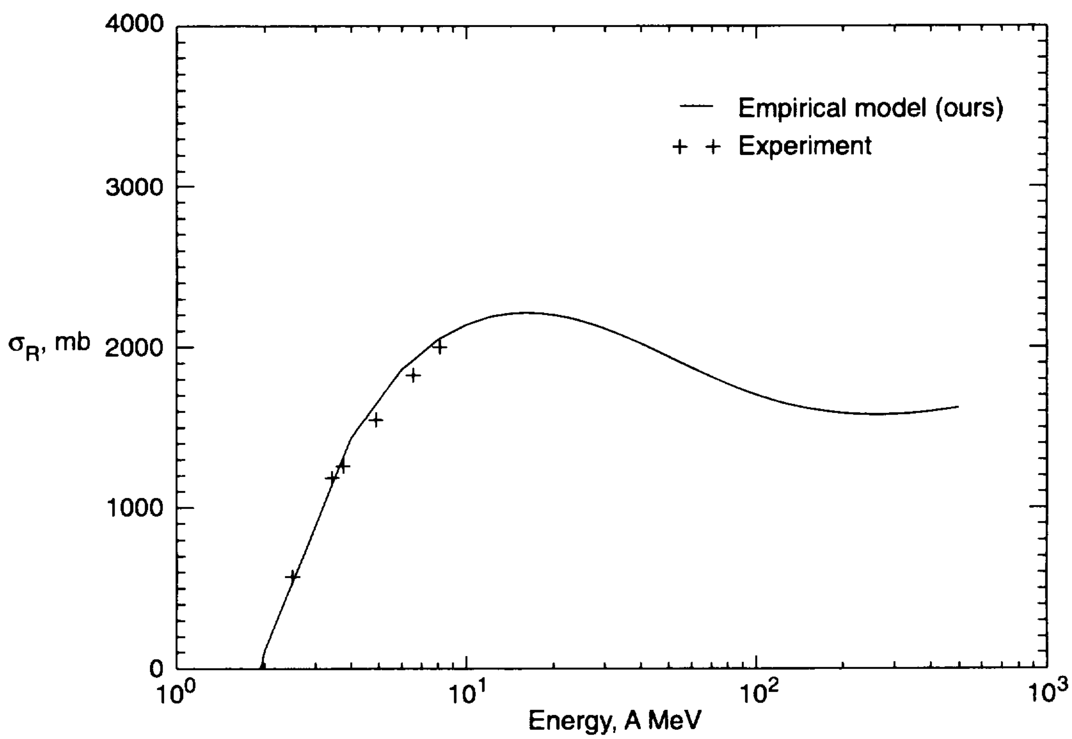


Figure 24. Reaction cross sections as a function of energy for ${}^{16}_{8}O + {}^{40}_{20}Ca$ collisions.

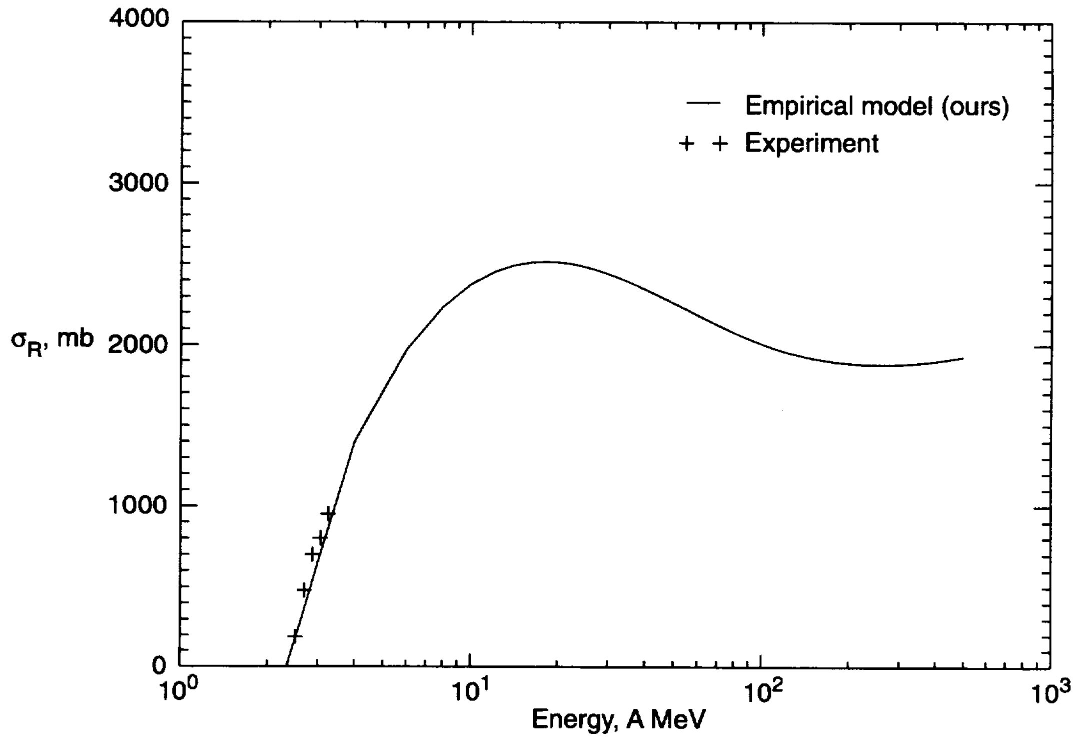


Figure 25. Reaction cross sections as a function of energy for ${}^{16}_{8}O + {}^{59}_{27}Co$ collisions.

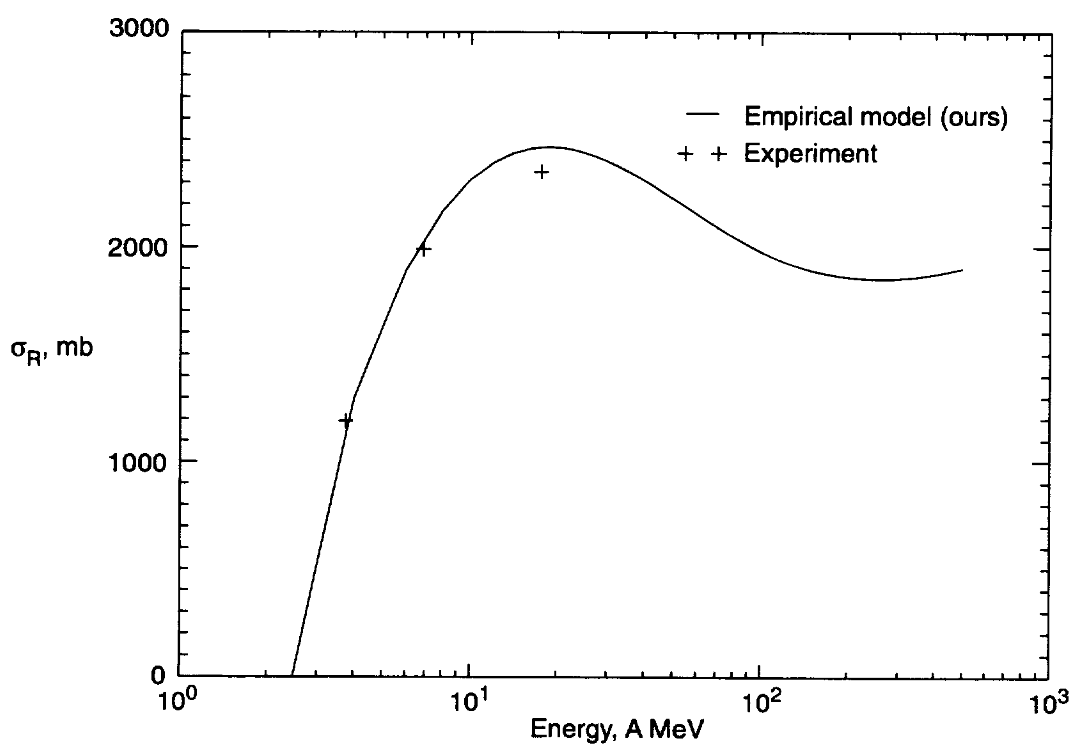


Figure 26. Reaction cross sections as a function of energy for ${}^{16}_{8}O + {}^{58}_{28}Ni$ collisions.

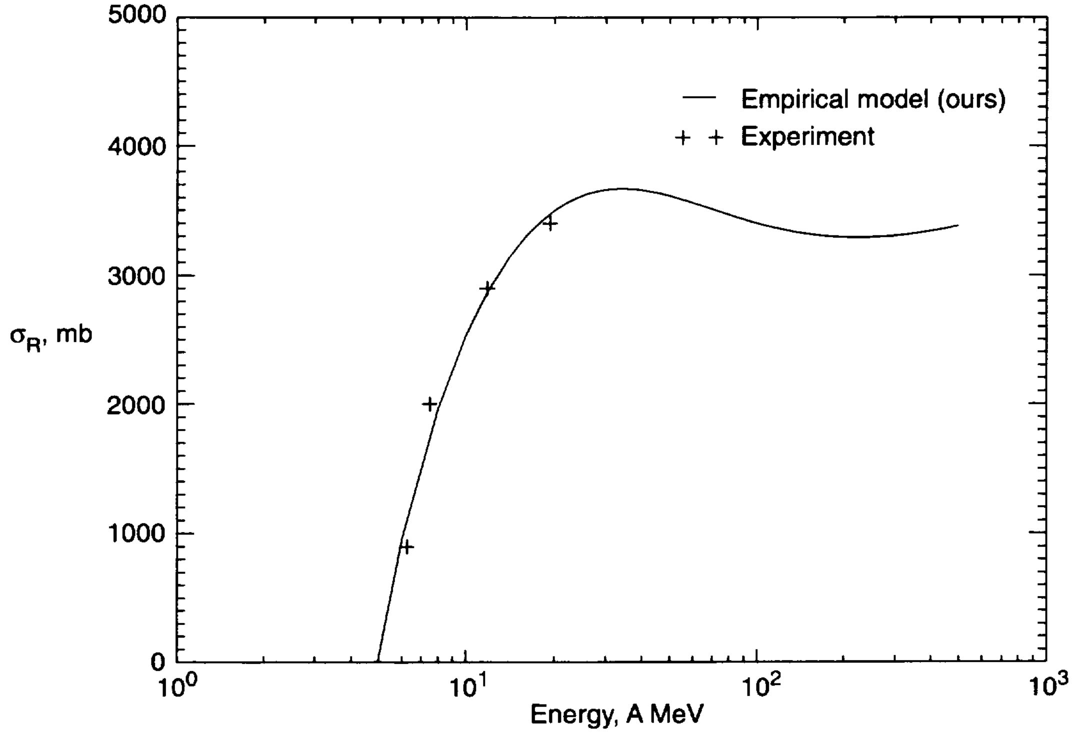


Figure 27. Reaction cross sections as a function of energy for ${}^{16}_{8}O + {}^{208}_{82}Pb$ collisions.

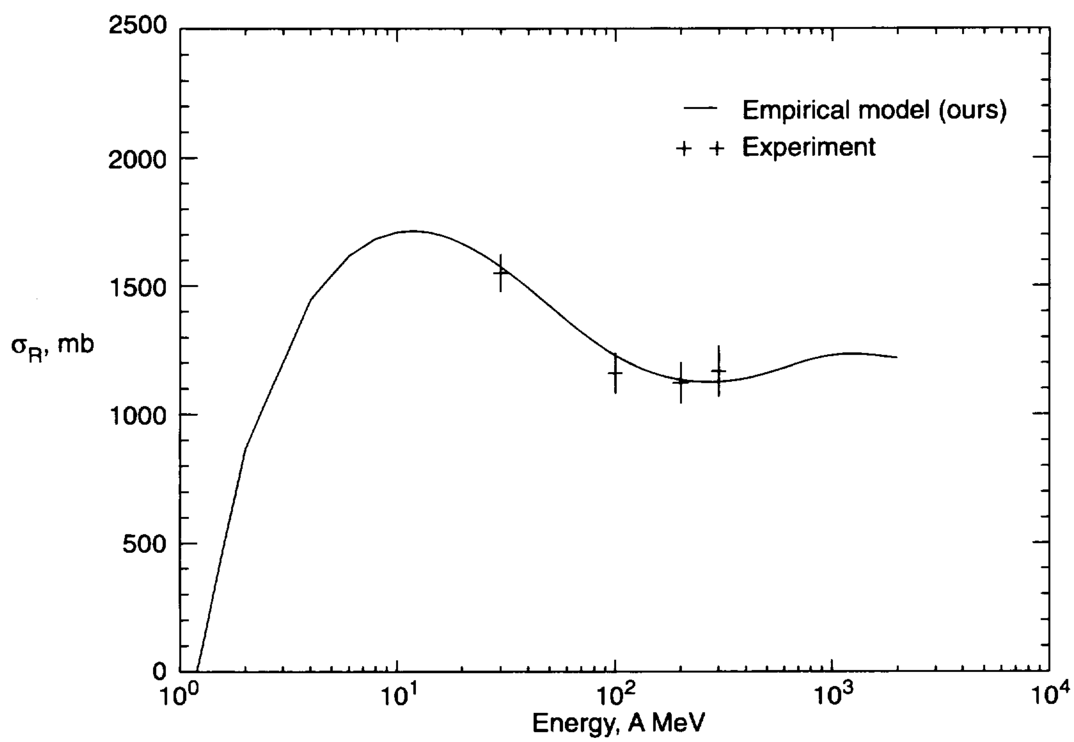


Figure 28. Reaction cross sections as a function of energy for ${}^{20}_{10}Ne + {}^{12}_{6}C$ collisions.

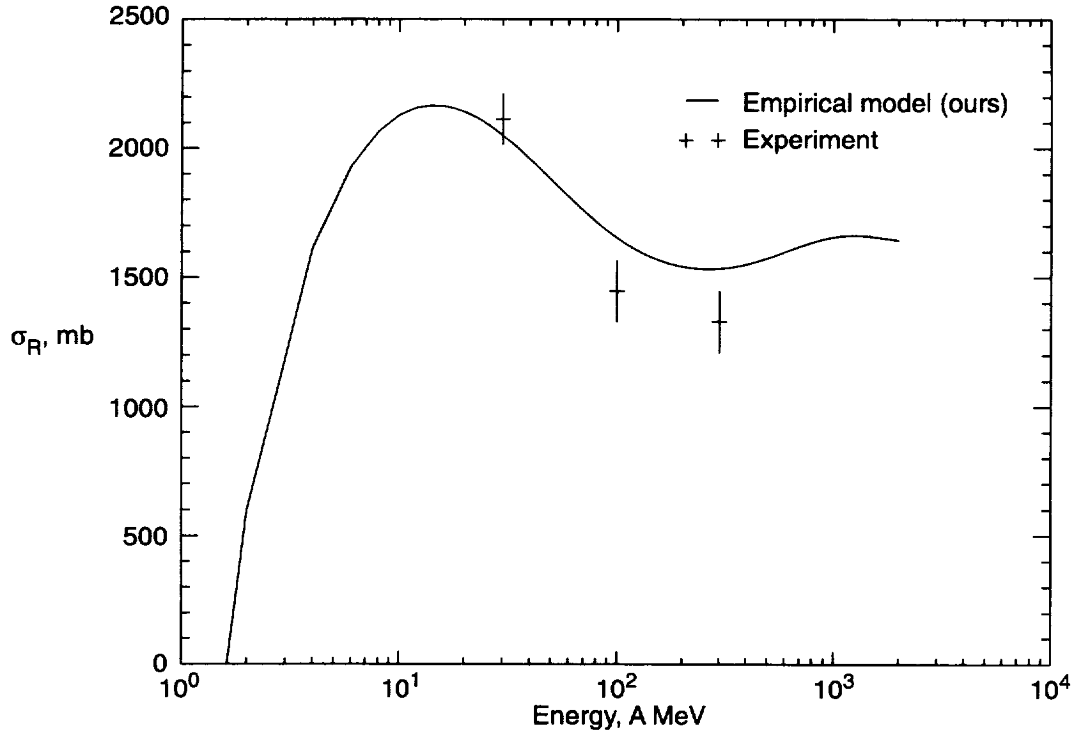


Figure 29. Reaction cross sections as a function of energy for ${}^{20}_{10}Ne + {}^{27}_{13}Al$ collisions.

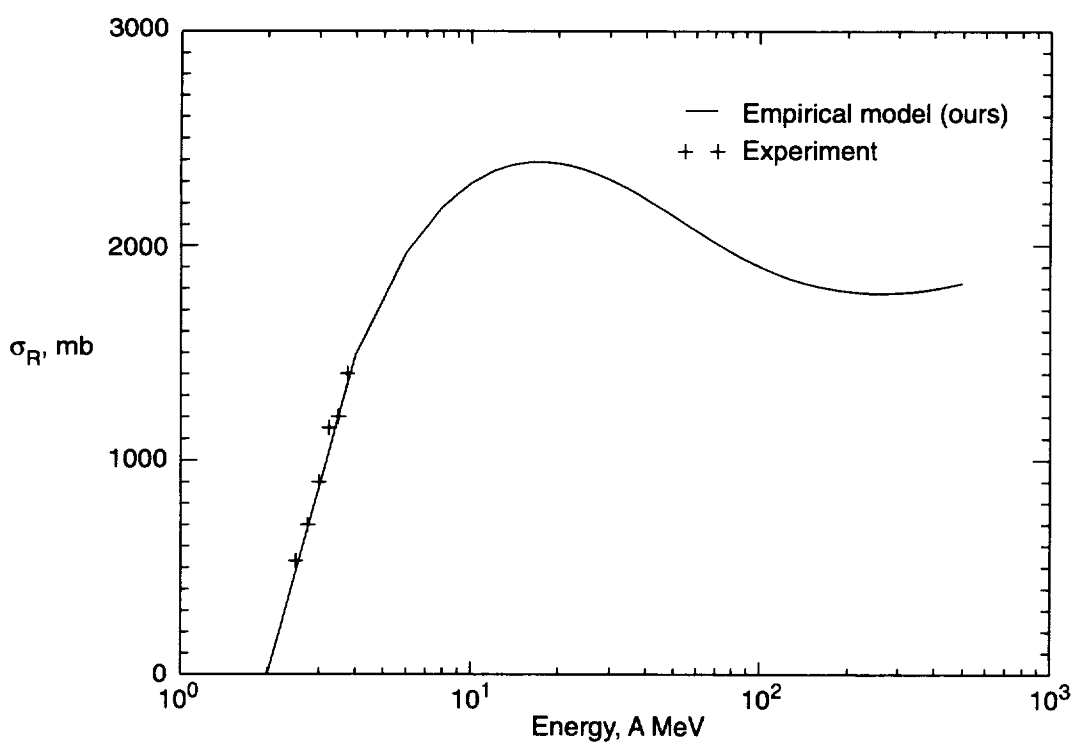


Figure 30. Reaction cross sections as a function of energy for ${}^{20}_{10}Ne + {}^{40}_{20}Ca$ collisions.

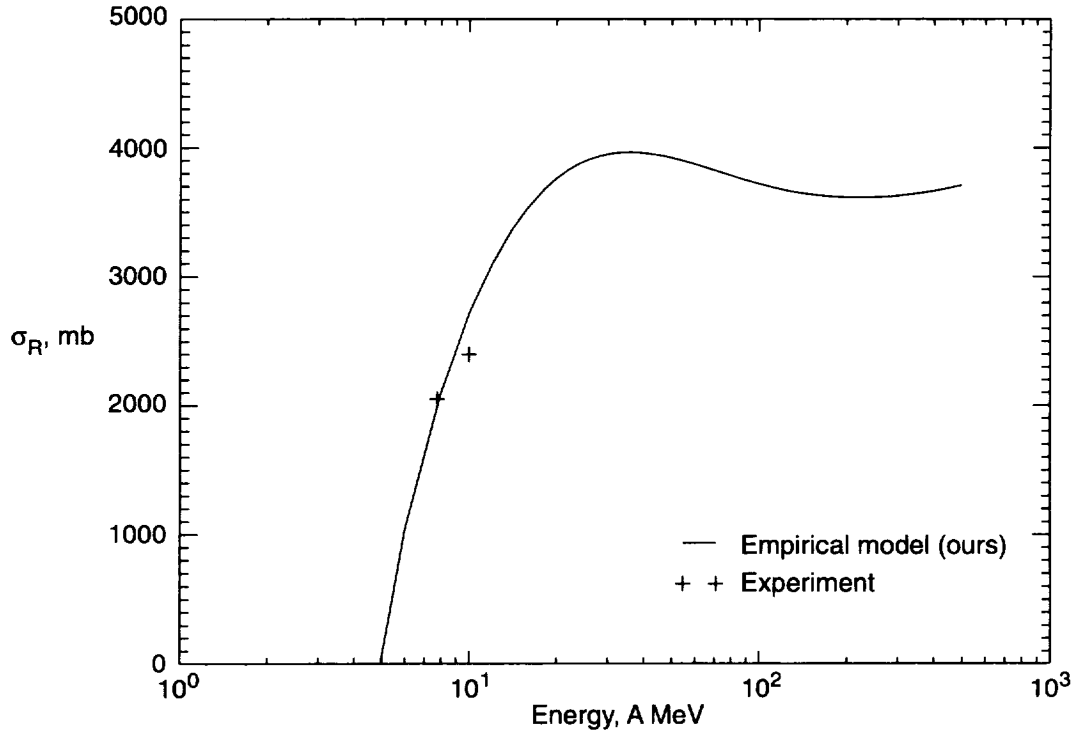


Figure 31. Reaction cross sections as a function of energy for ${}^{20}_{10}Ne + {}^{208}_{82}Pb$ collisions.

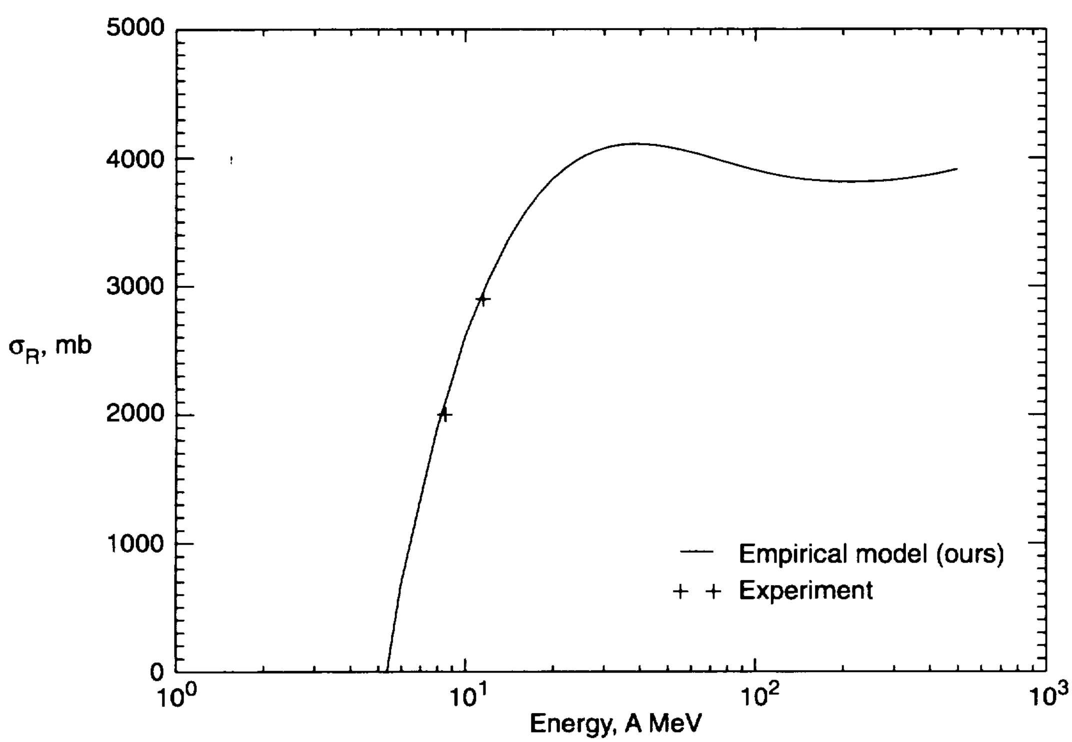


Figure 32. Reaction cross sections as a function of energy for ${}^{20}_{10}Ne + {}^{235}_{92}U$ collisions.

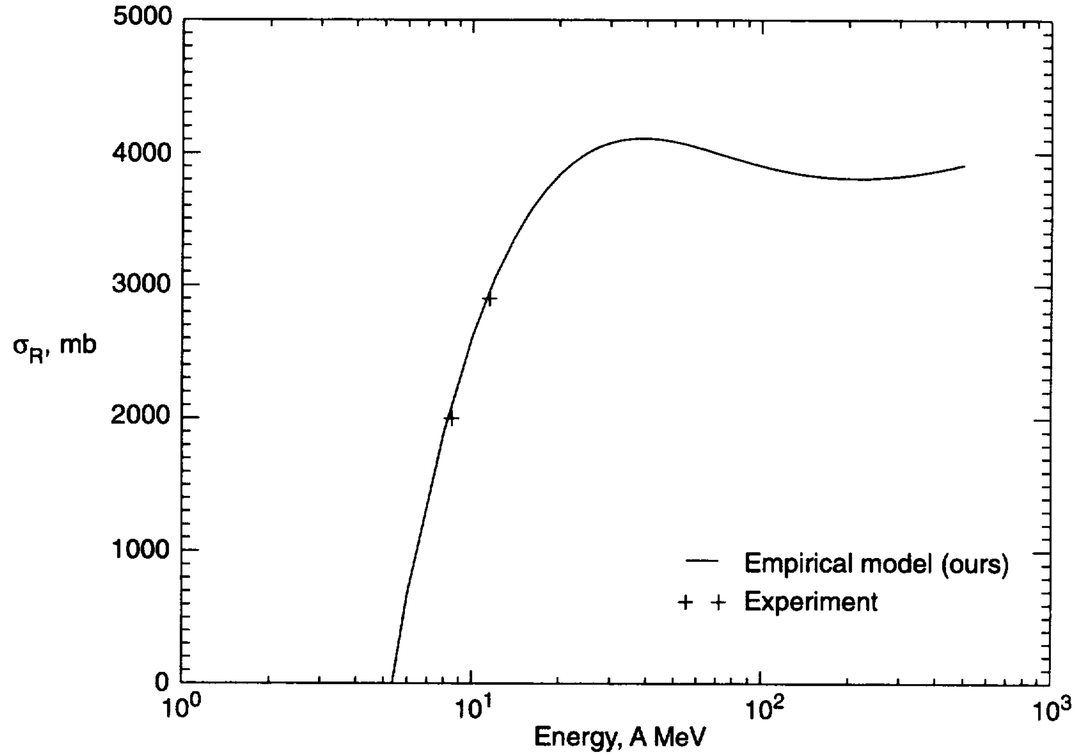


Figure 33. Reaction cross sections as a function of energy for ${}^{32}_{16}S + {}^{24}_{12}Mg$ collisions.

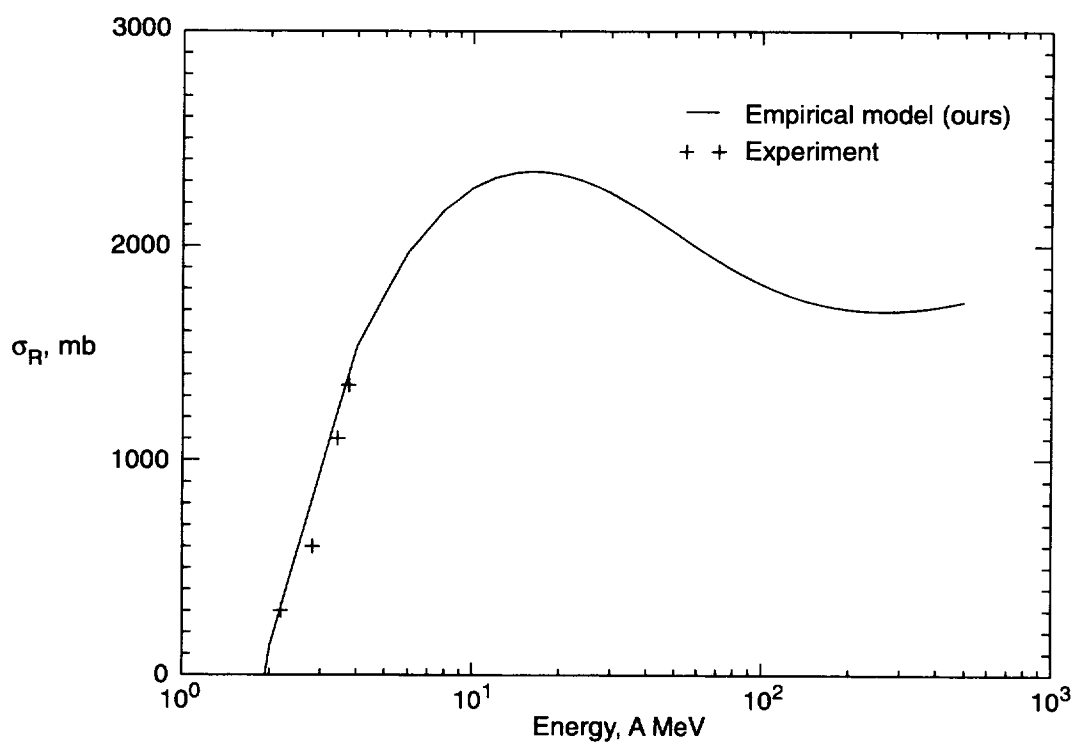


Figure 34. Reaction cross sections as a function of energy for ${}^{32}_{16}S + {}^{27}_{13}Al$ collisions.

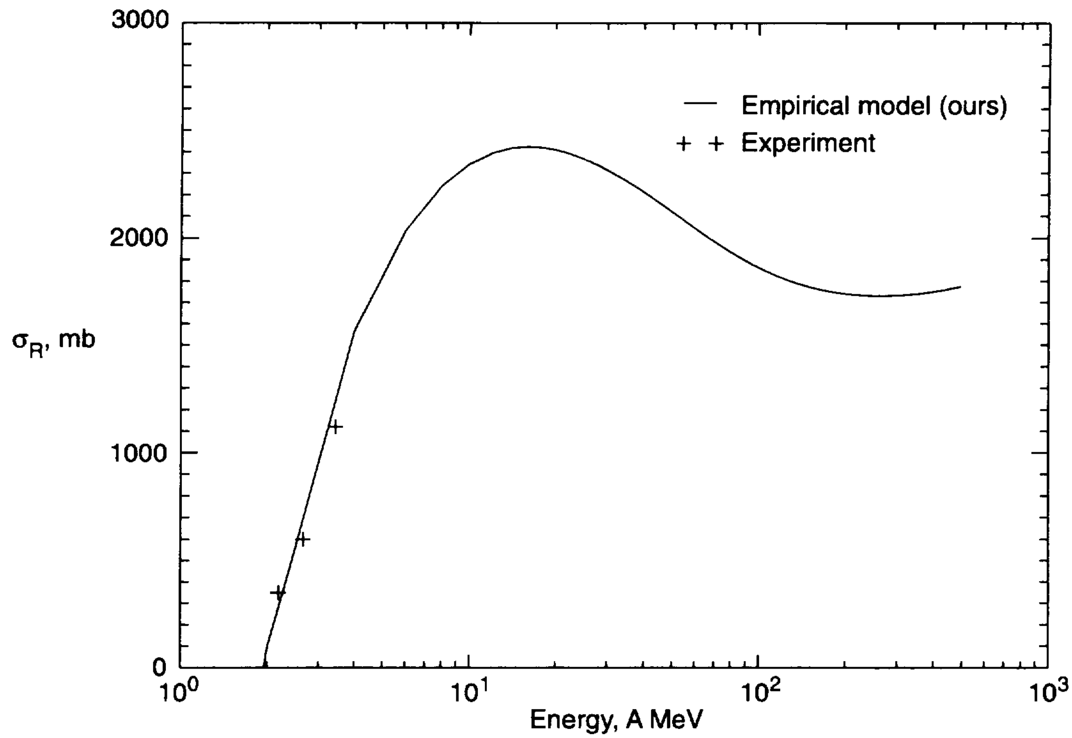


Figure 35. Reaction cross sections as a function of energy for ${}^{35}_{17}Cl + {}^{58}_{28}Ni$ collisions.

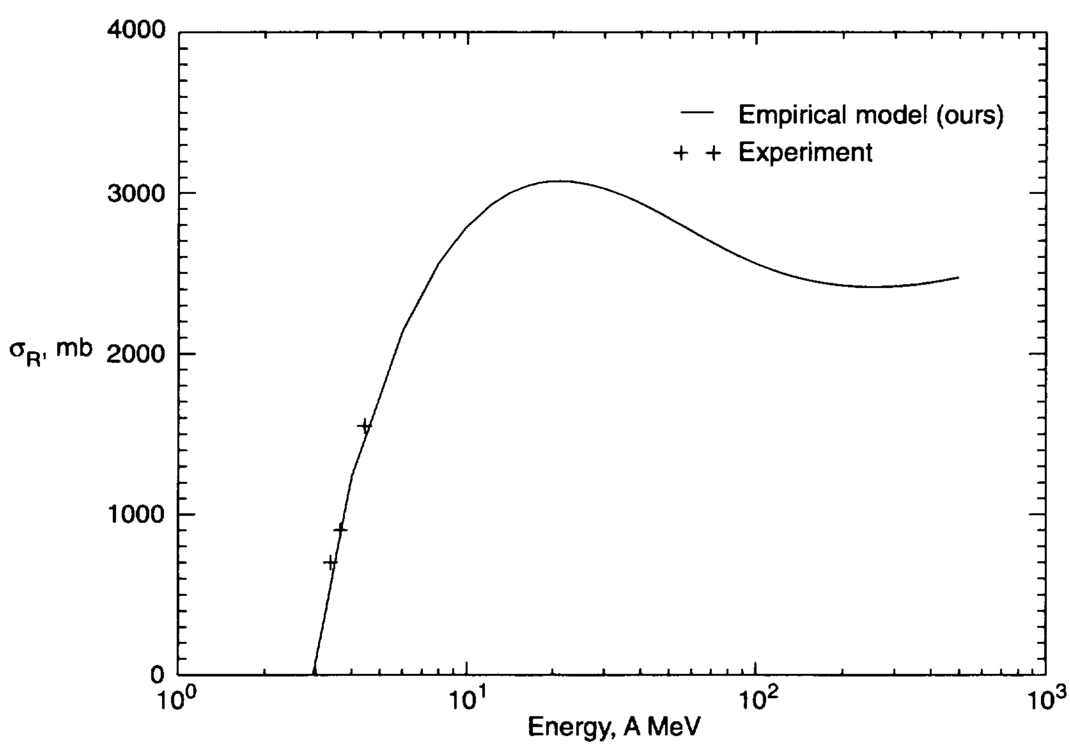


Figure 36. Reaction cross sections as a function of energy for ${}^{35}_{17}Cl + {}^{62}_{28}Ni$ collisions.

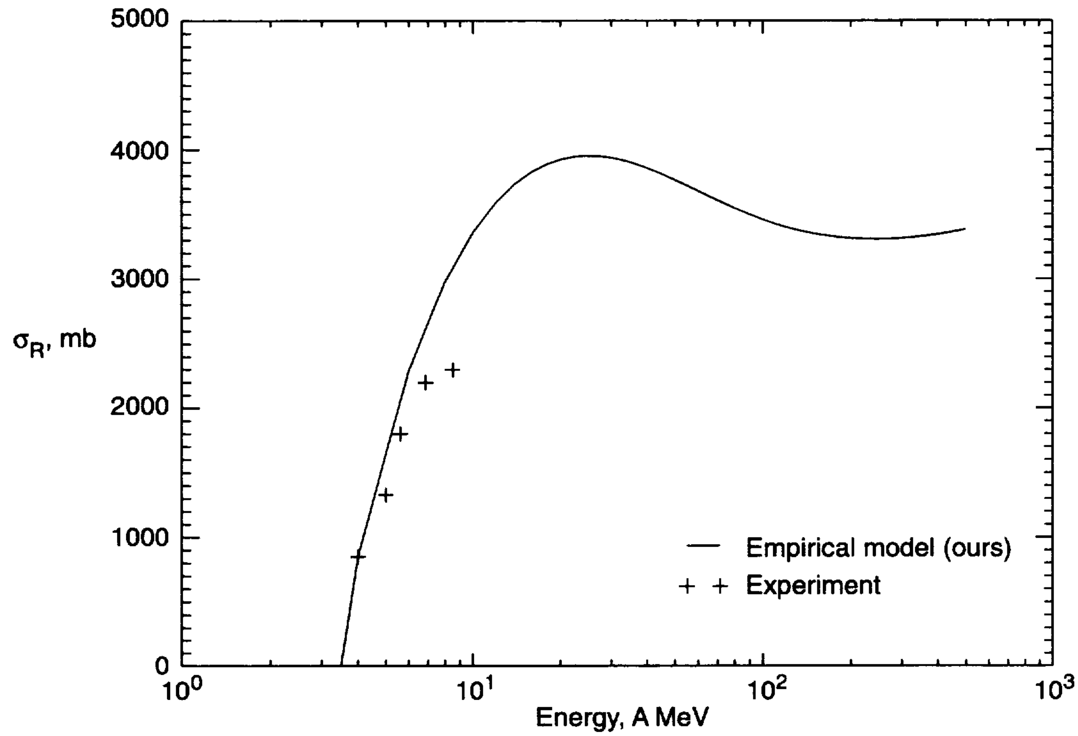


Figure 37. Reaction cross sections as a function of energy for $^{40}_{18}Ar + ^{109}_{47}Ag$ collisions.

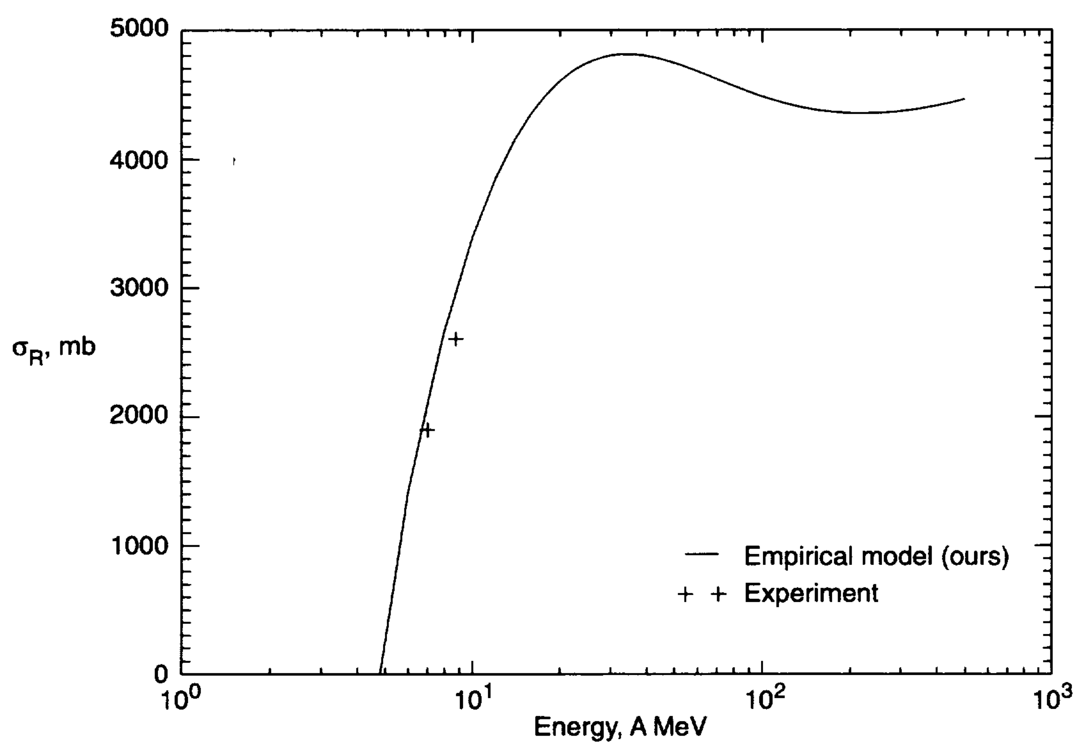


Figure 38. Reaction cross sections as a function of energy for $^{40}_{18}Ar + ^{209}_{83}Bi$ collisions.

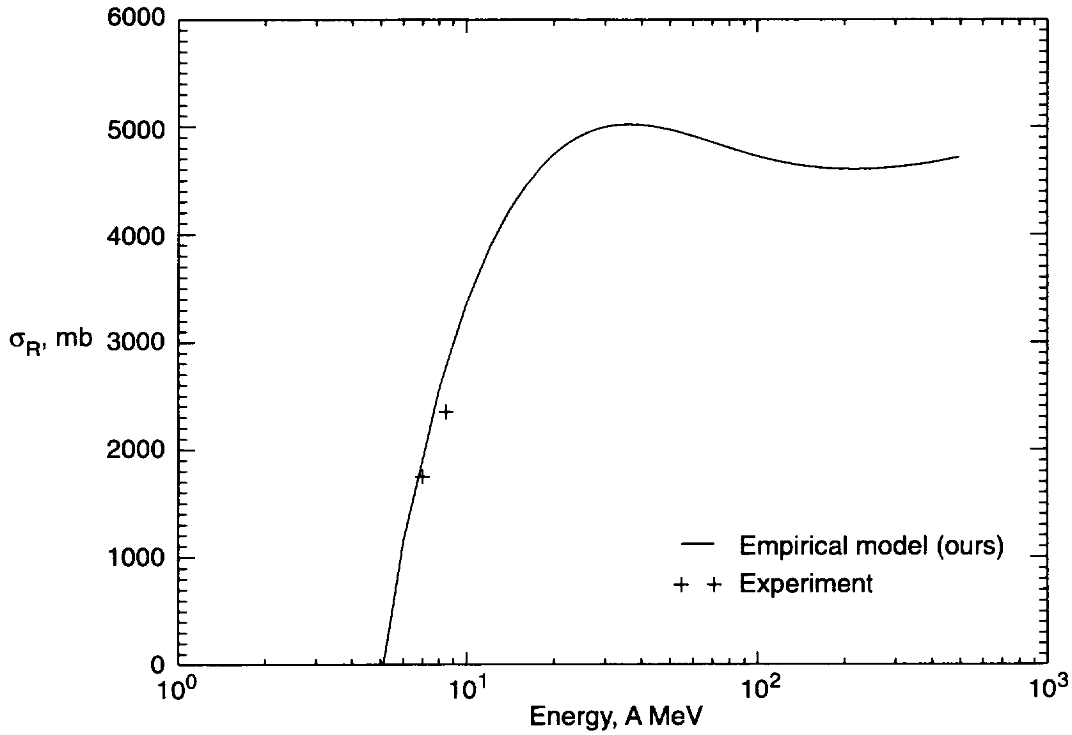


Figure 39. Reaction cross sections as a function of energy for ${}^{40}_{18}Ar + {}^{238}_{92}U$ collisions.

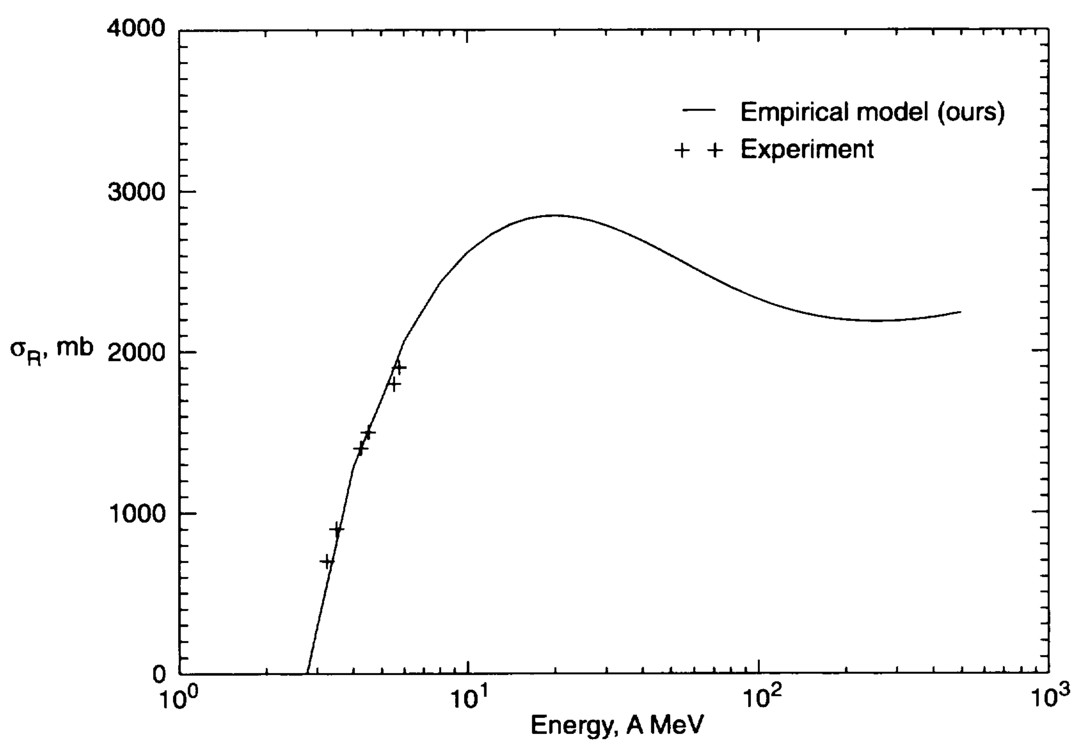


Figure 40. Reaction cross sections as a function of energy for ${}^{40}_{20}Ca + {}^{40}_{20}Ca$ collisions.

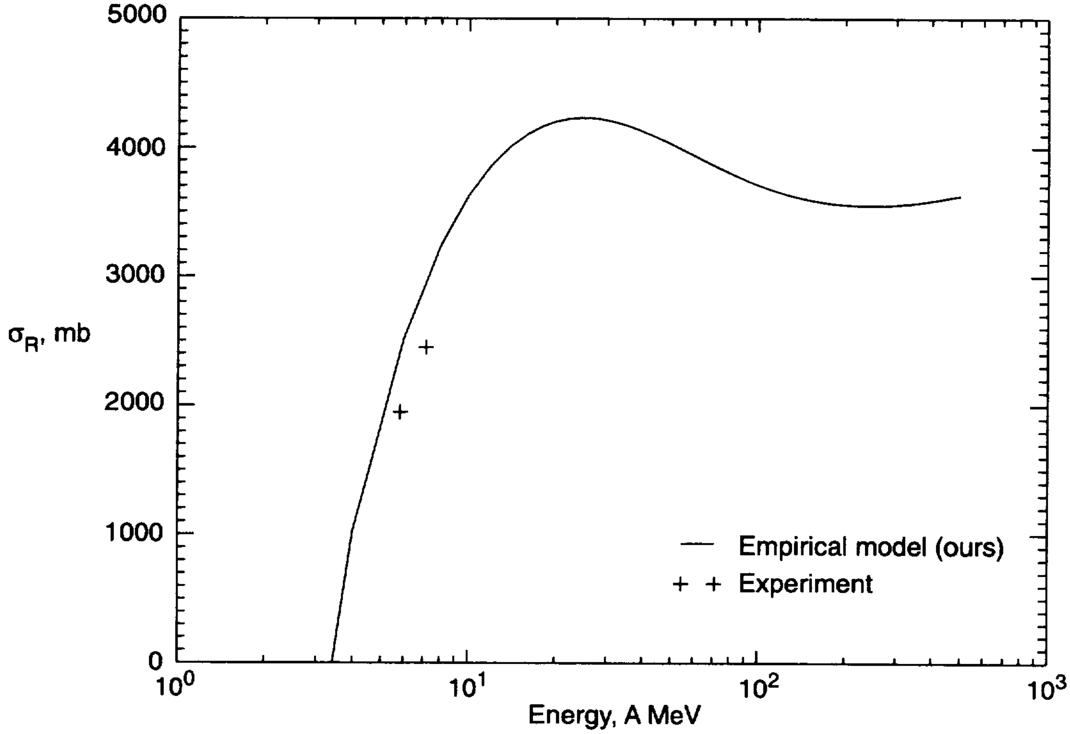


Figure 41. Reaction cross sections as a function of energy for ${}^{84}_{36}Kr + {}^{65}_{29}Cu$ collisions.

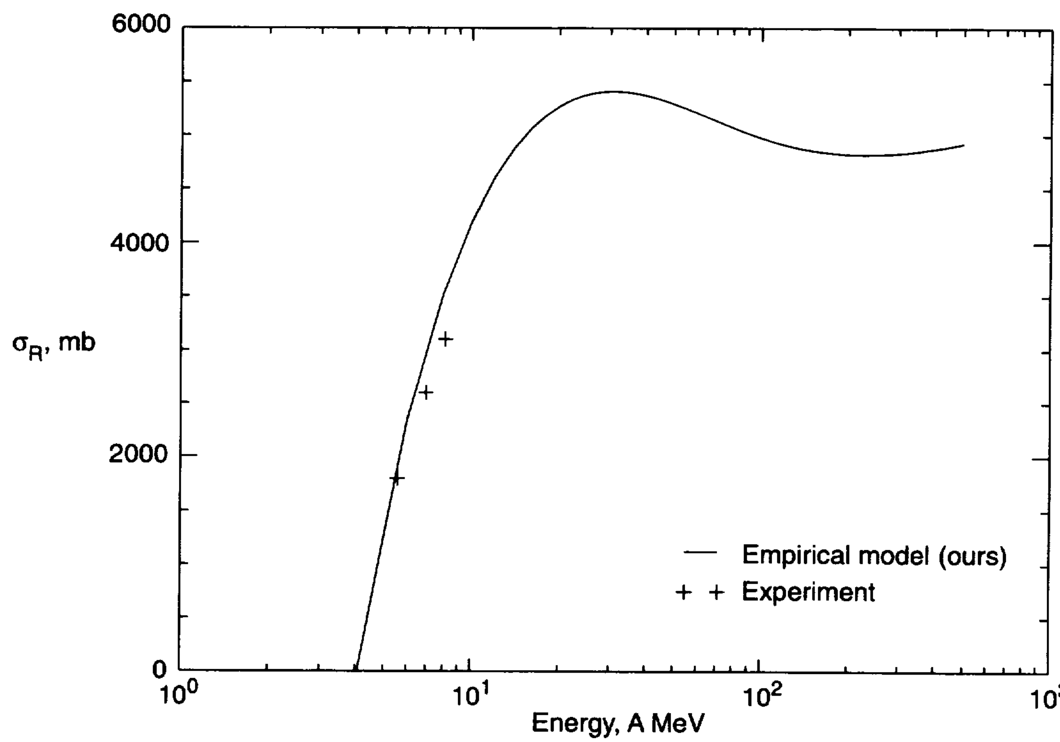


Figure 42. Reaction cross sections as a function of energy for ${}^{86}_{36}Kr + {}^{139}_{57}La$ collisions.

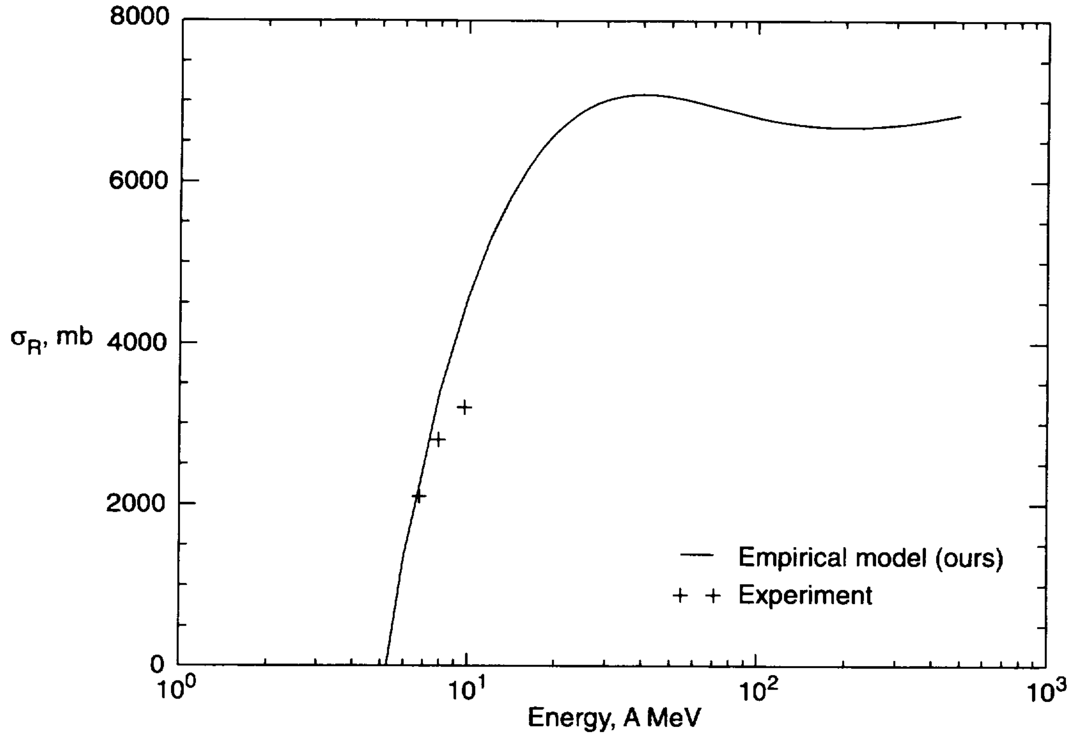


Figure 43. Reaction cross sections as a function of energy for ${}^{136}_{54}Xe + {}^{209}_{83}Bi$ collisions.

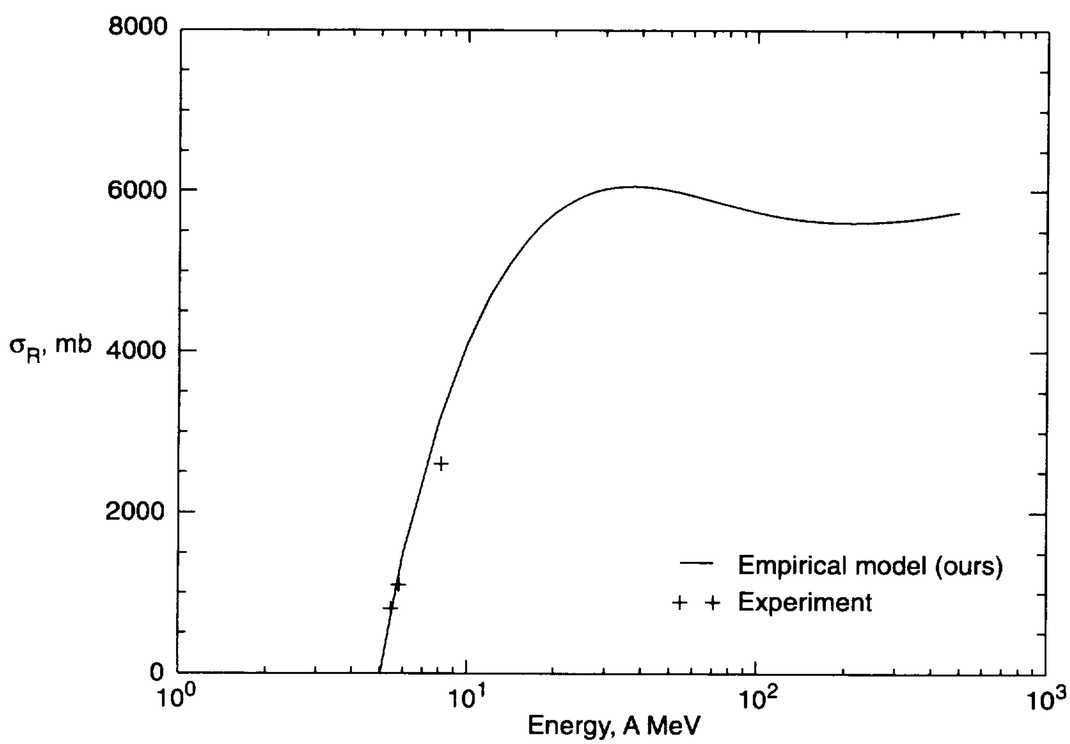


Figure 44. Reaction cross sections as a function of energy for ${}^{84}_{36}Kr + {}^{208}_{82}Pb$ collisions.

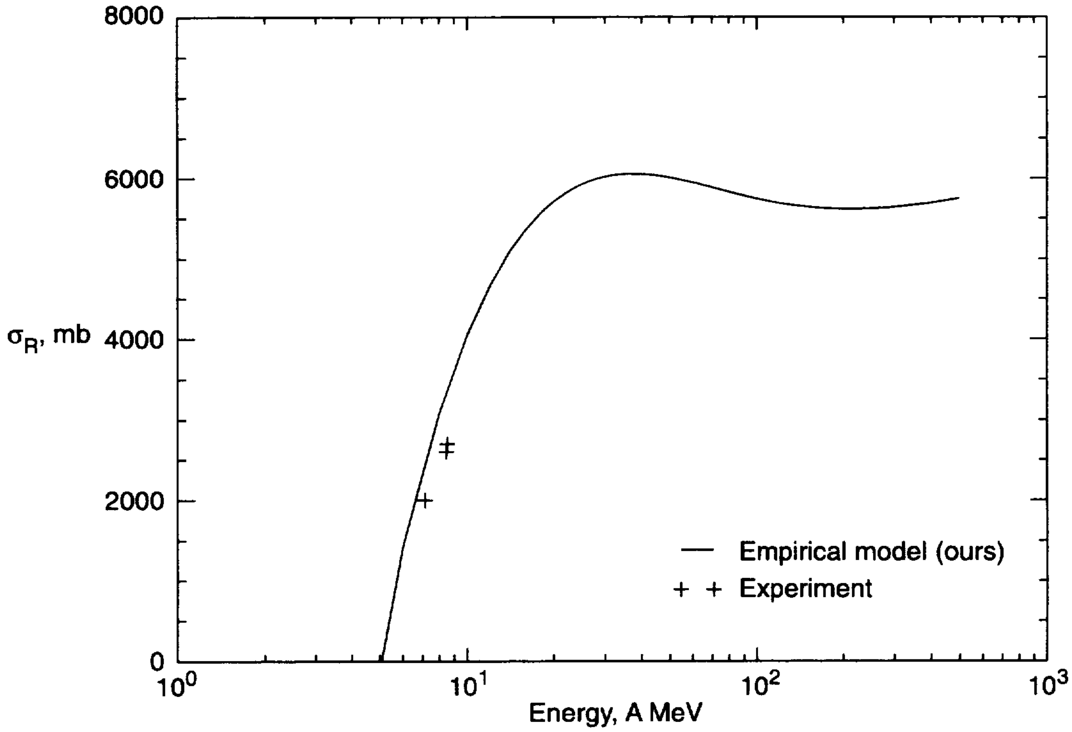


Figure 45. Reaction cross sections as a function of energy for ${}^{84}_{36}Kr + {}^{209}_{83}Bi$ collisions.

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
January 1997

3. REPORT TYPE AND DATES COVERED
Technical Paper

4. TITLE AND SUBTITLE
Universal Parameterization of Absorption Cross Sections

5. FUNDING NUMBERS
WU 199-45-16-11

6. AUTHOR(S)
R. K. Tripathi, Francis A. Cucinotta, and John W. Wilson

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, VA 23681-0001

8. PERFORMING ORGANIZATION REPORT NUMBER
L-17580

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TP-3621

11. SUPPLEMENTARY NOTES
Tripathi: Southern Illinois University, Carbondale, IL; Cucinotta and Wilson: NASA Langley Research Center, Hampton, VA.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified–Unlimited
Subject Category ~~93~~ 73
Availability: NASA CASI (301) 621-0390

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
This paper presents a simple universal parameterization of total reaction cross sections for any system of colliding nuclei that is valid for the entire energy range from a few AMeV to a few AGeV. The universal picture presented here treats proton-nucleus collision as a special case of nucleus-nucleus collision, where the projectile has charge and mass number of one. The parameters are associated with the physics of the collision system. In general terms, Coulomb interaction modifies cross sections at lower energies, and the effects of Pauli blocking are important at higher energies. The agreement between the calculated and experimental data is better than all earlier published results.

14. SUBJECT TERMS
Nuclear reaction; Cross sections; Heavy ions

15. NUMBER OF PAGES
27

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102